Photometric Calibration for the Large Synoptic Survey Telescope (LSST)

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Peter Yoachim, Tim Axelrod,
Jim Bartlett, Gurvan Bazin, Guillaume Blanc, Alexandre Boucaud,
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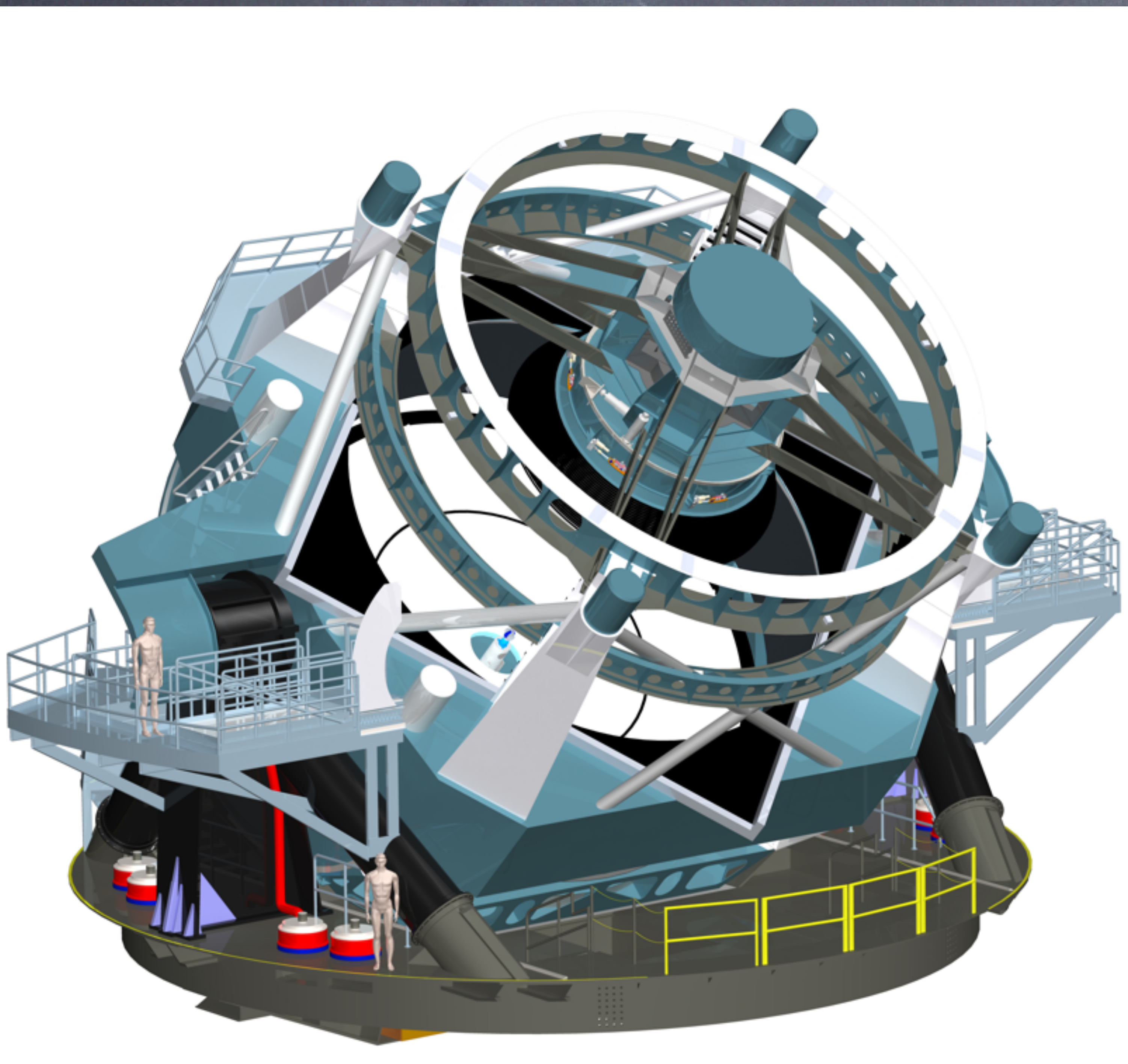
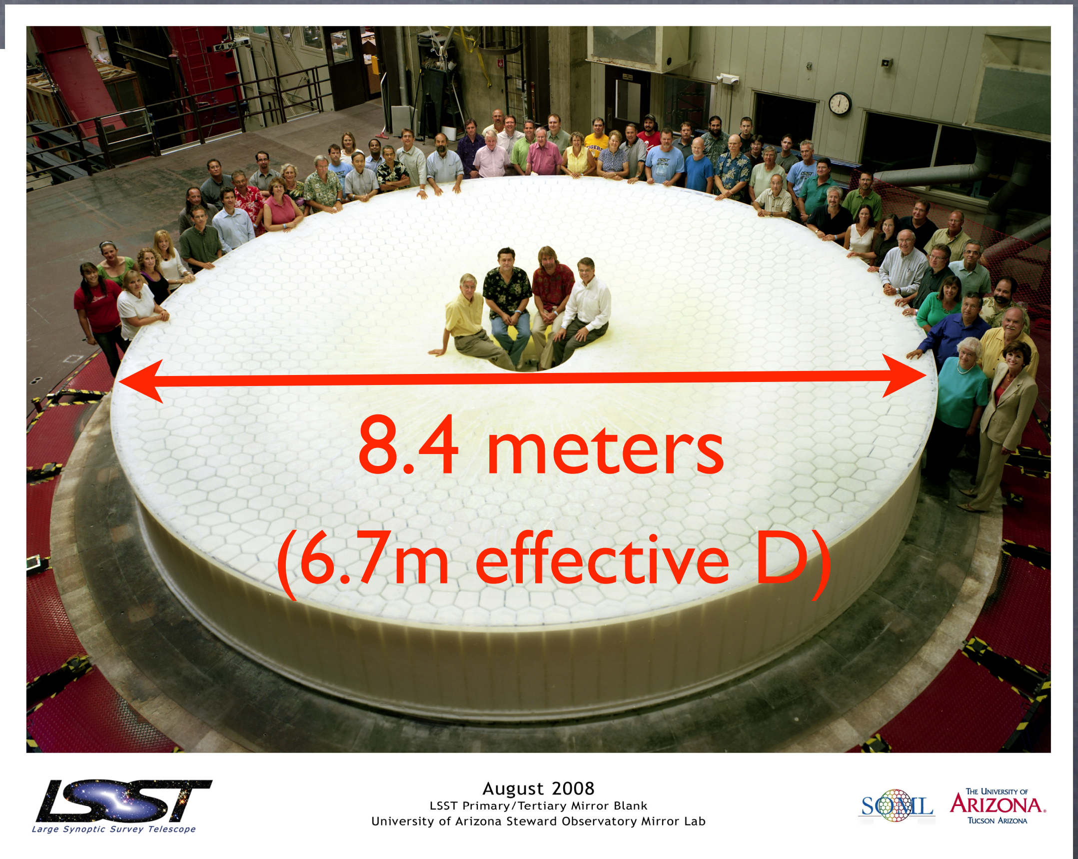
Cecile Roucelle, Abi Saha,Allyn Smith,
Chris Smith, Michael Strauss, Chris Stubbs, and
LSST Photometric Calibration Team

FNAL   April 19, 2012

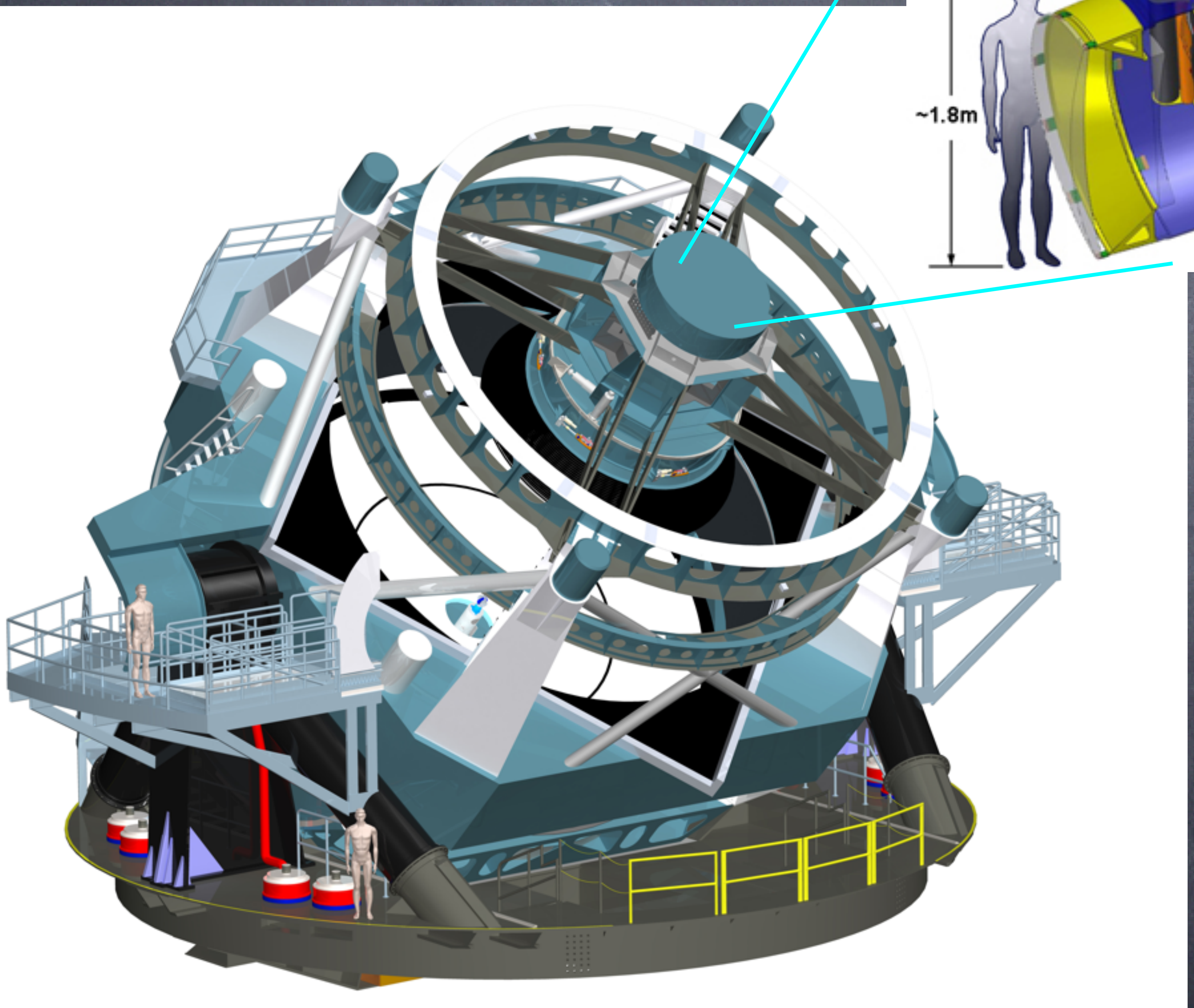
What is LSST?

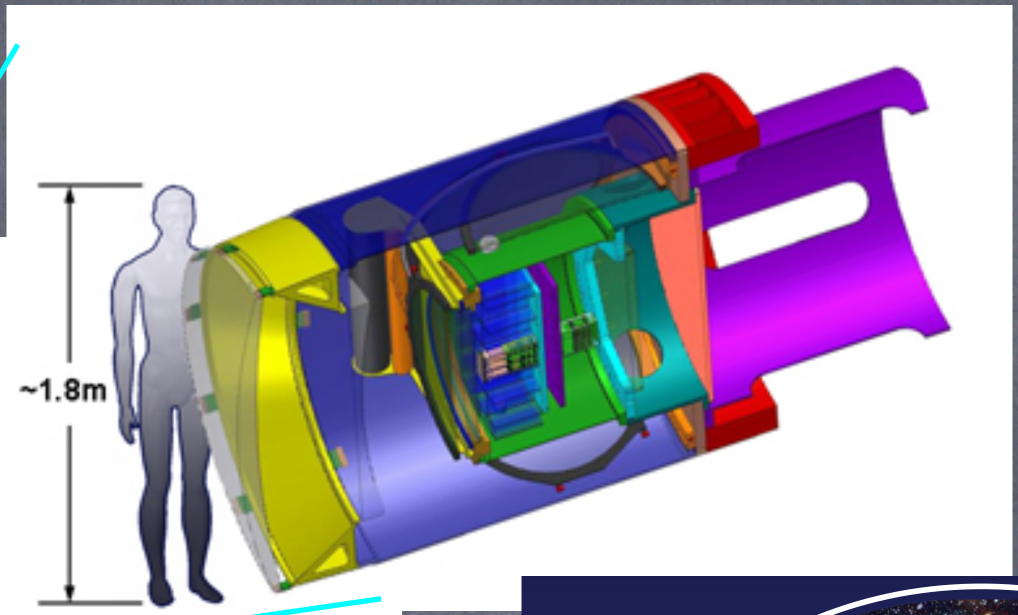


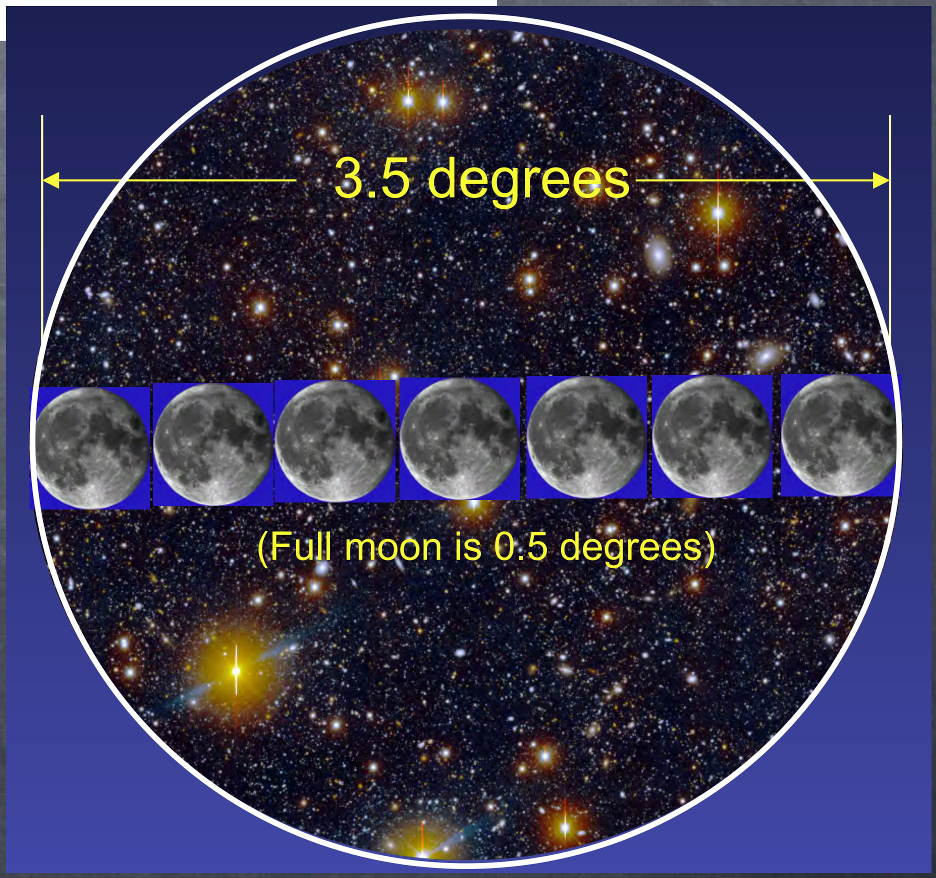


8.4 meters
(6.7m effective D)
Large Synoptic Survey Telescope
August 2008
LSST Primary/Tertiary Mirror Blank
University of Arizona Steward Observatory Mirror Lab
The University of Arizona
Tucson Arizona

What is LSST?

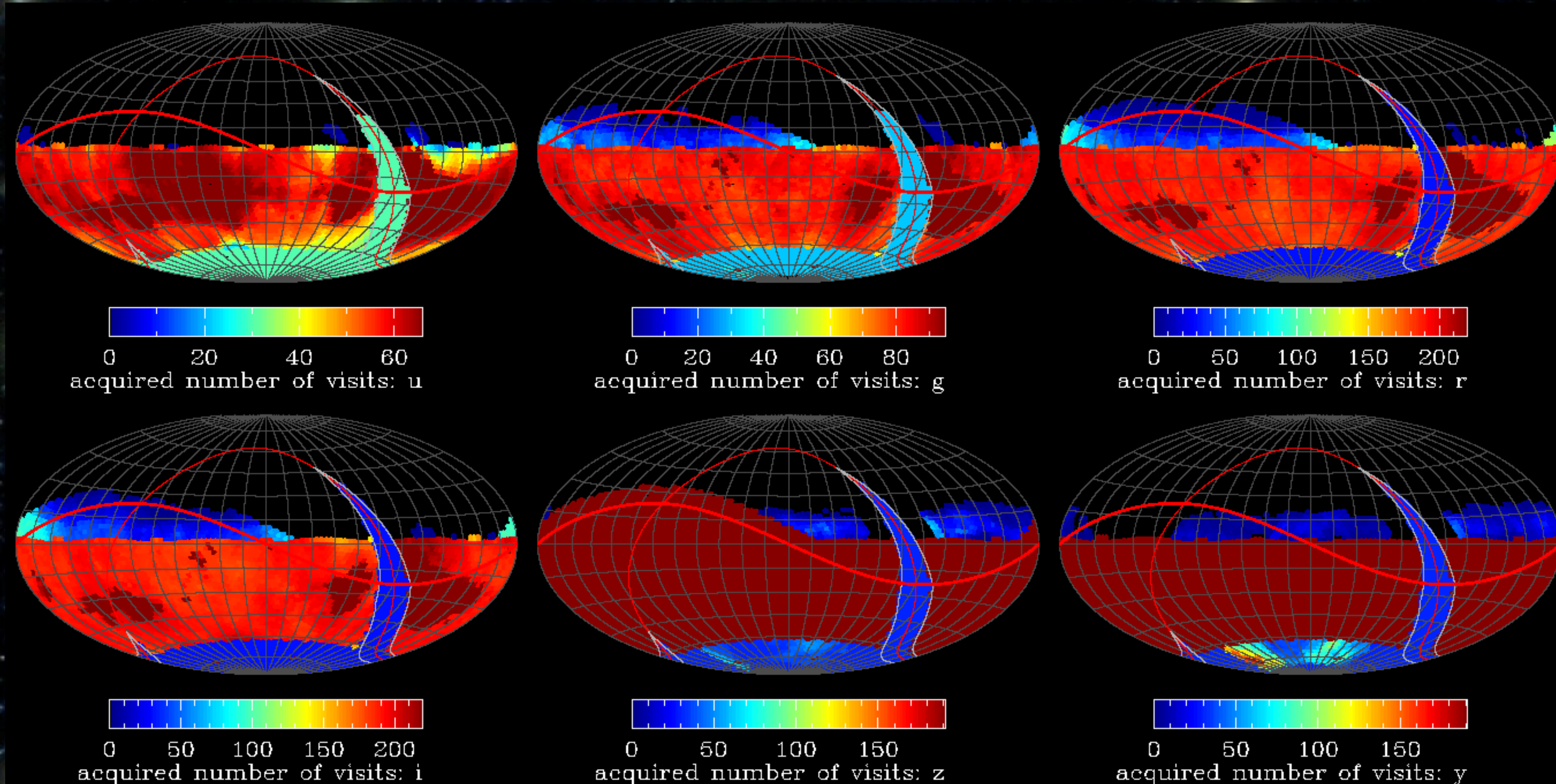






Science goals

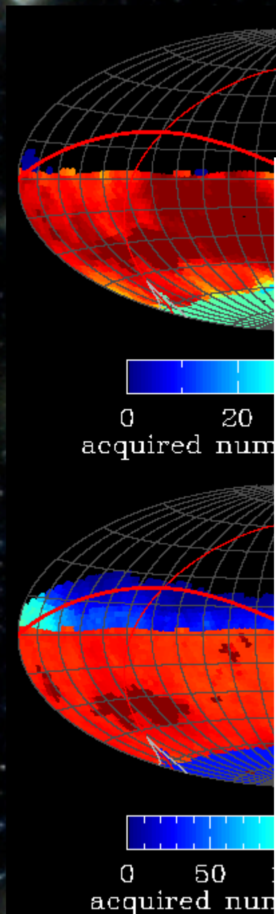
- 4 primary 'science drivers'
  - Explore dark energy and dark matter 10B galaxies
  - Map the Milky Way and the Local Volume 10B stars
  - Explore the 'transient sky' (transients and variables) 1000x observations
  - Inventory the Solar System 11M small moving objects

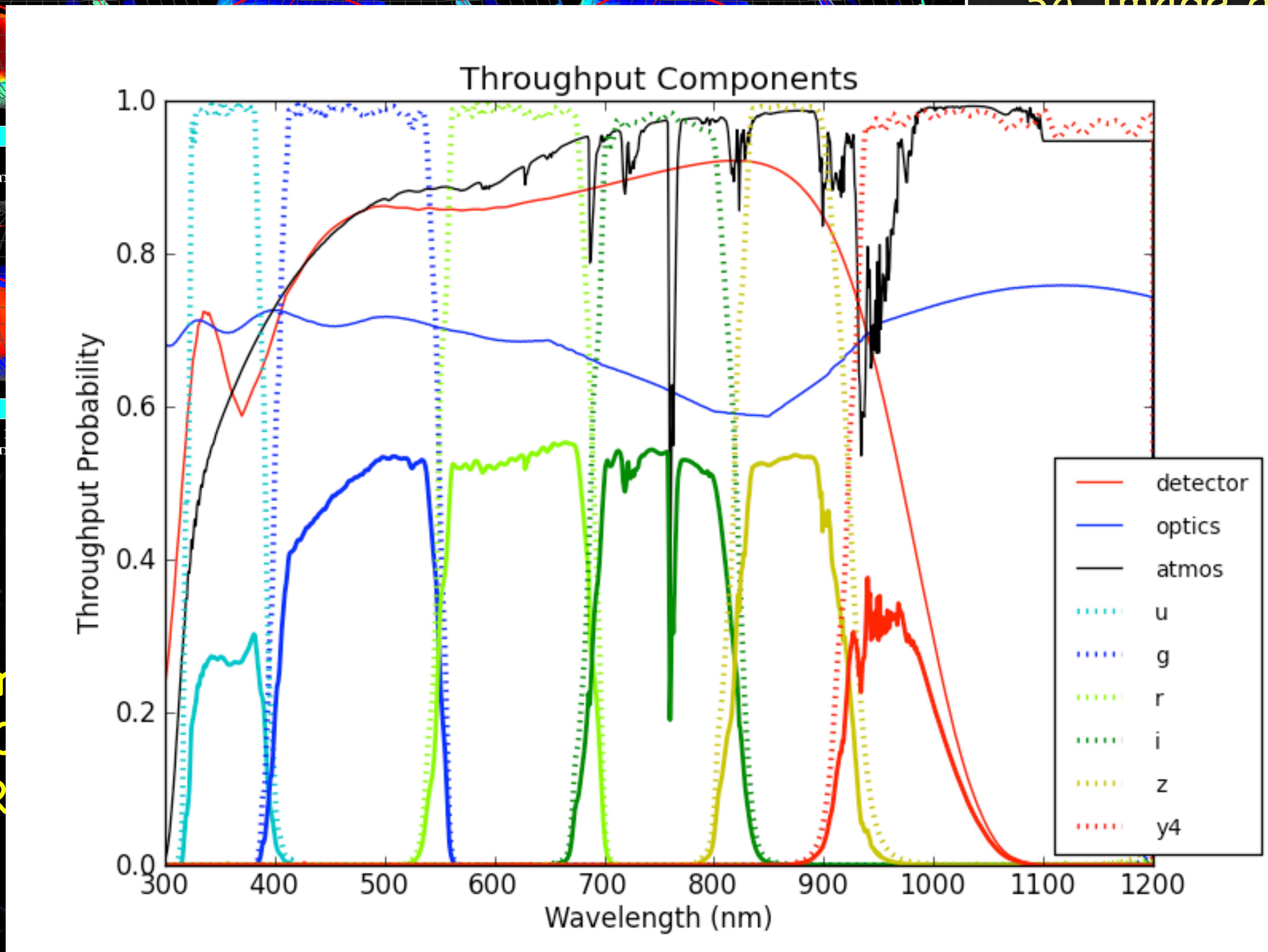


5σ Image depth		
Filter	Visit	Coadd
u	23.9	26.3
g	25.0	27.5
r	24.7	27.7
i	24.0	27.0
z	23.3	26.2
y	22.1	24.9

'visit' = 2 x 15s exposures
~825 visits per field,
2 visits per night,
revisit visible sky 3-4 days,
18,000 square degrees for 10 years
Range of weather conditions

Photometric precision (mmag)		
	gri	uzy
Repeatability	5	7.5
Uniformity	10	15
Band-to-band	5	10
Astrometric precision (mas)		
Relative	10	





r
18,00
R

5σ Image depth
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26.3
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mmag)
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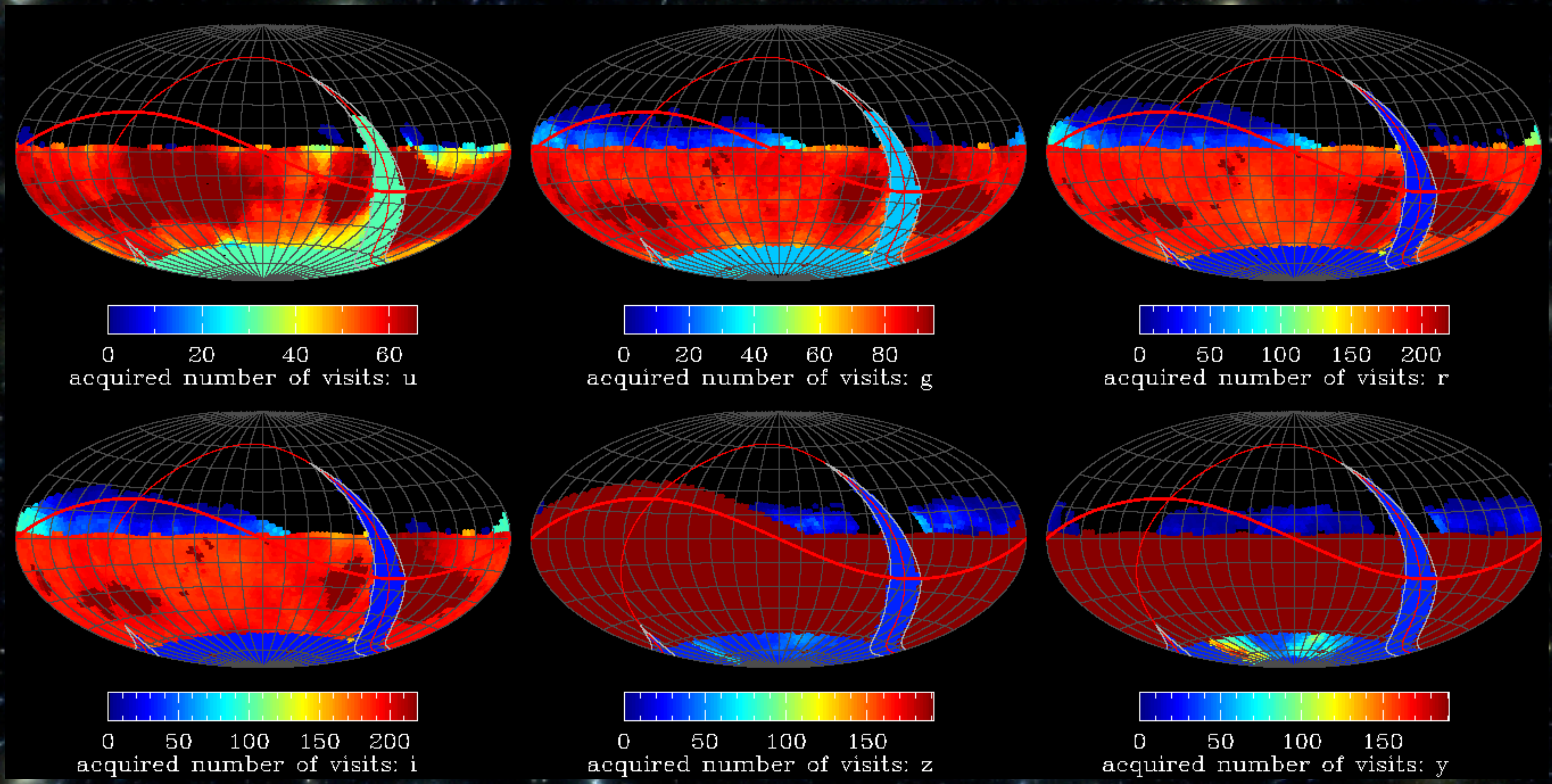

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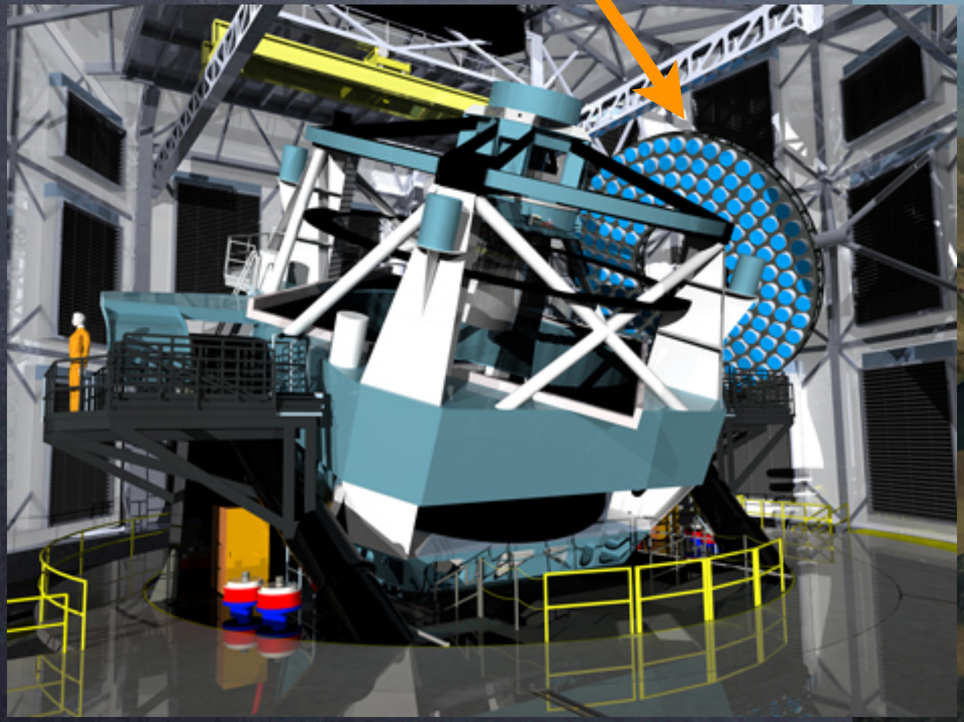
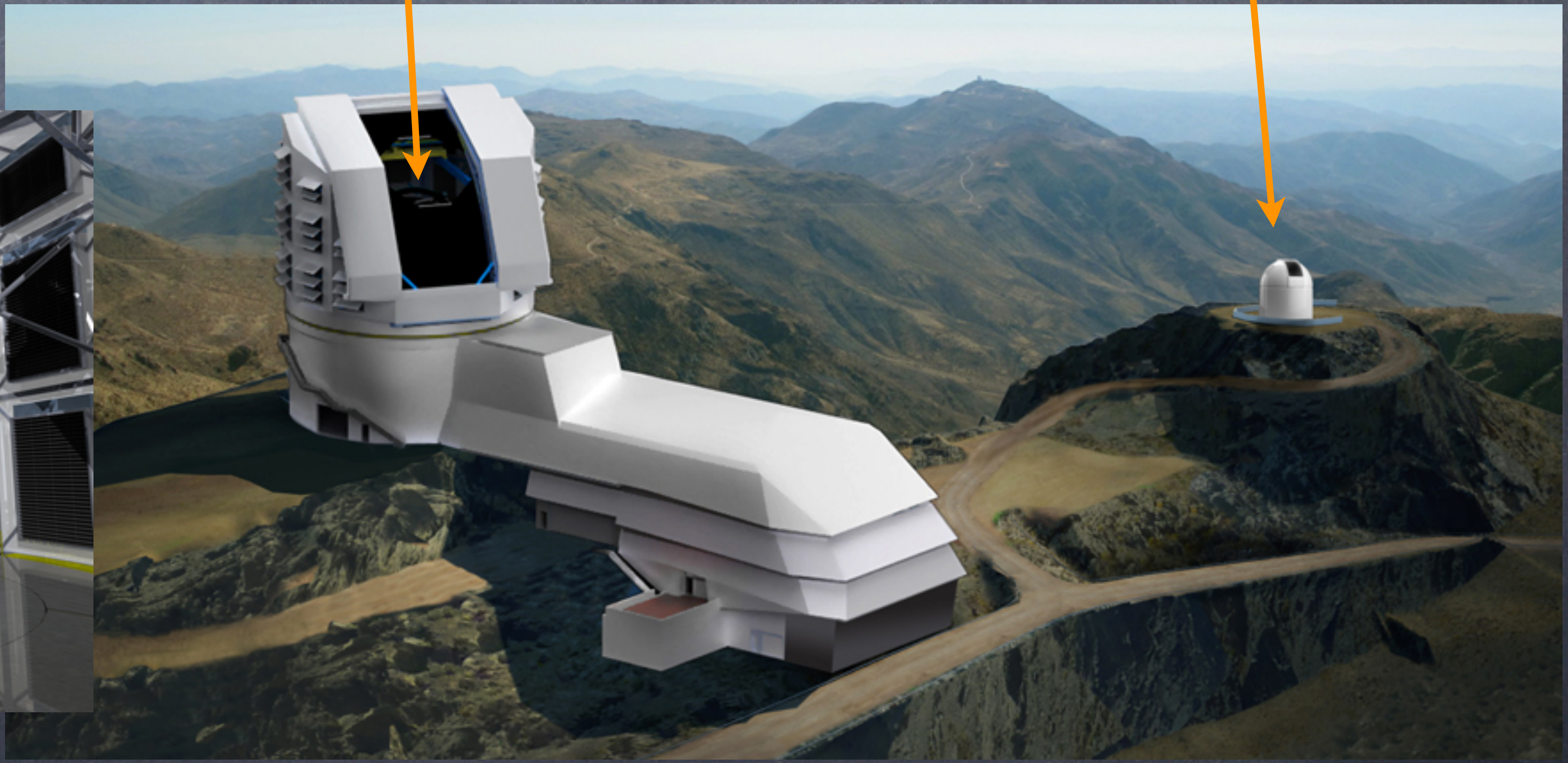
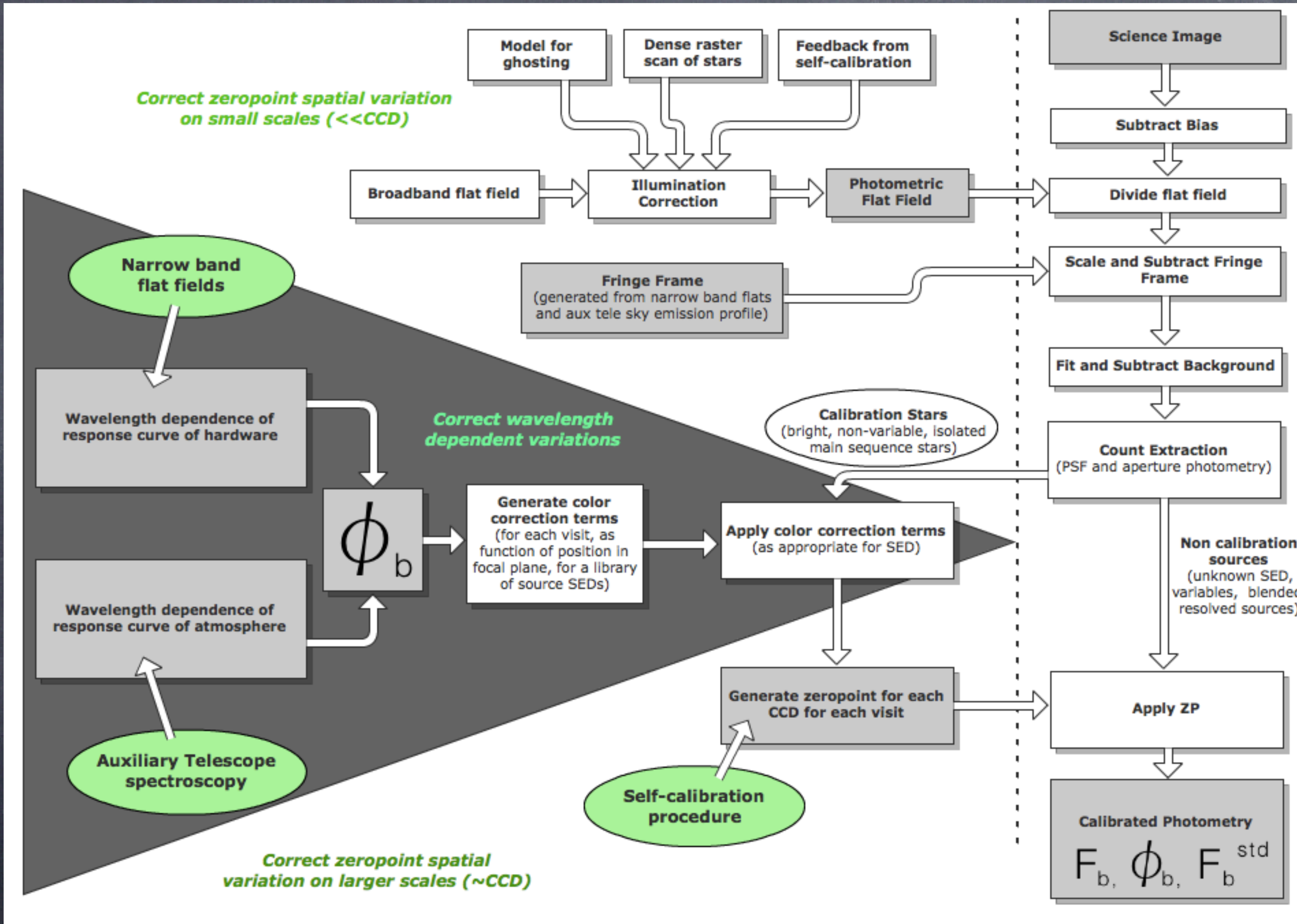
How can we achieve these calibration goals?

- Use optimized methods to measure hardware throughput and atmospheric throughput separately (and also measure wavelength-dependent and independent effects separately)
- Take advantage of many observations of many stars under a wide variety of conditions (self-calibration)

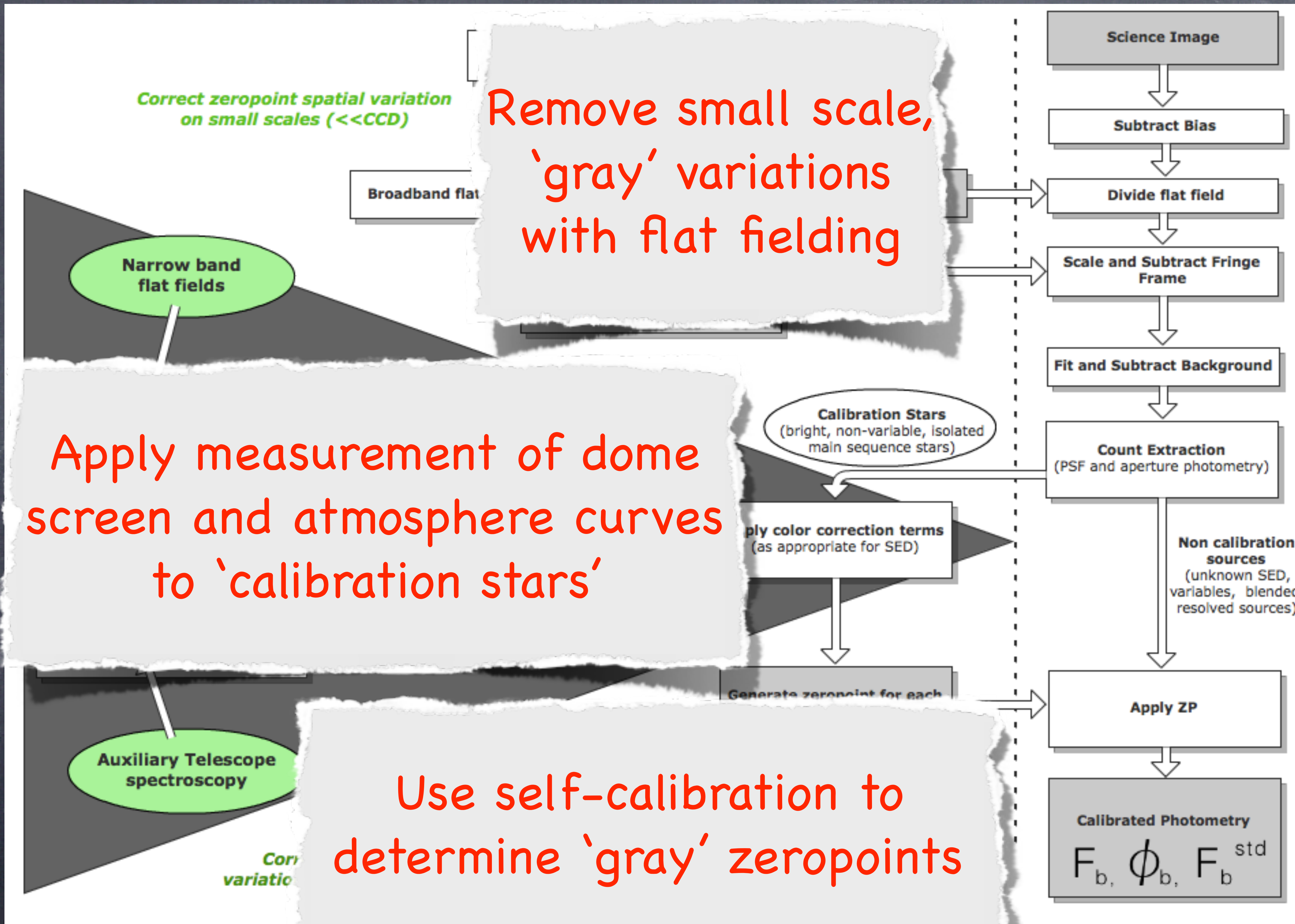




Flowchart of Internal Photometric Calibration



Flowchart of Internal Photometric Calibration

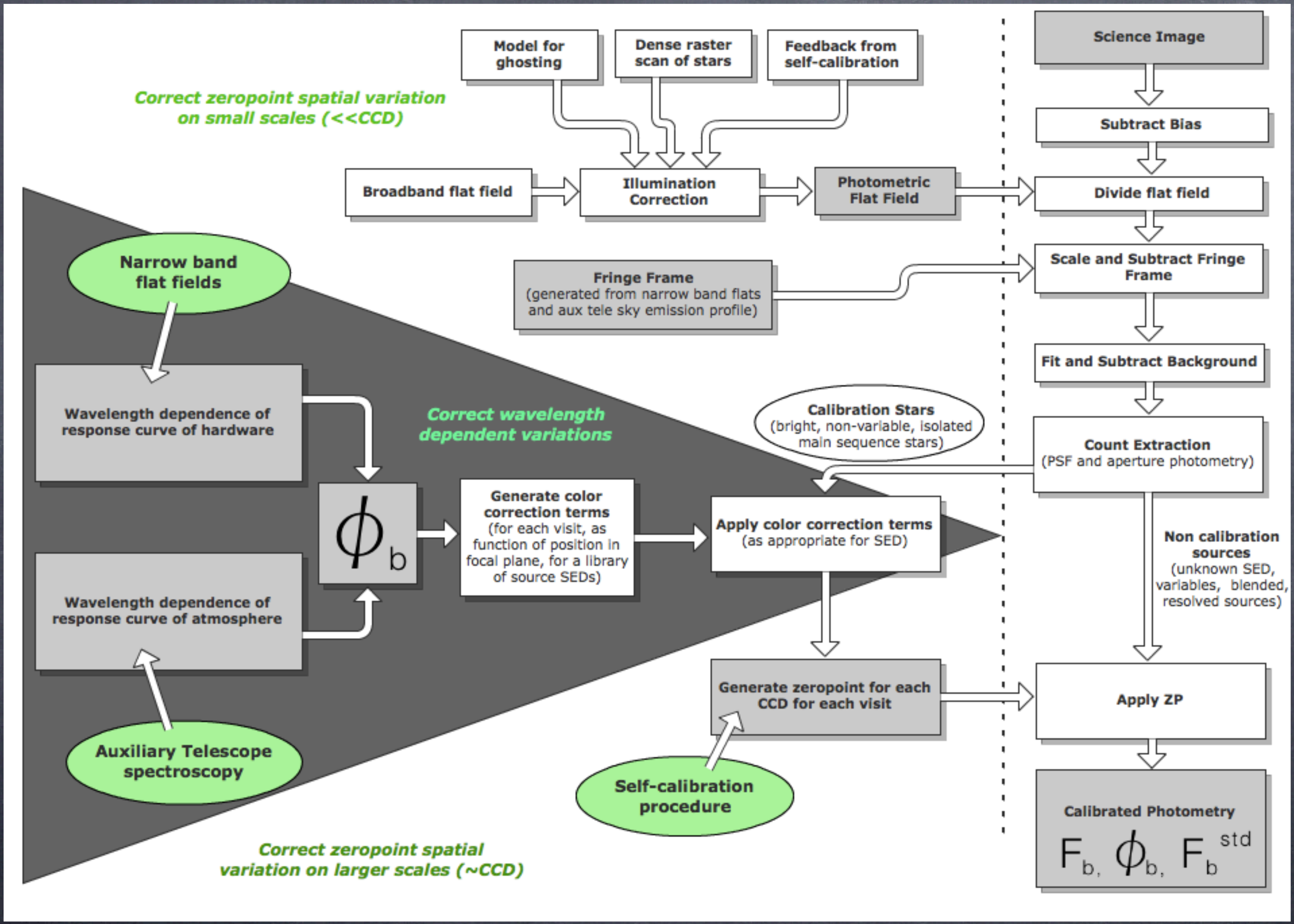


Remove small scale, 'gray' variations with flat fielding

Apply measurement of dome screen and atmosphere curves to 'calibration stars'

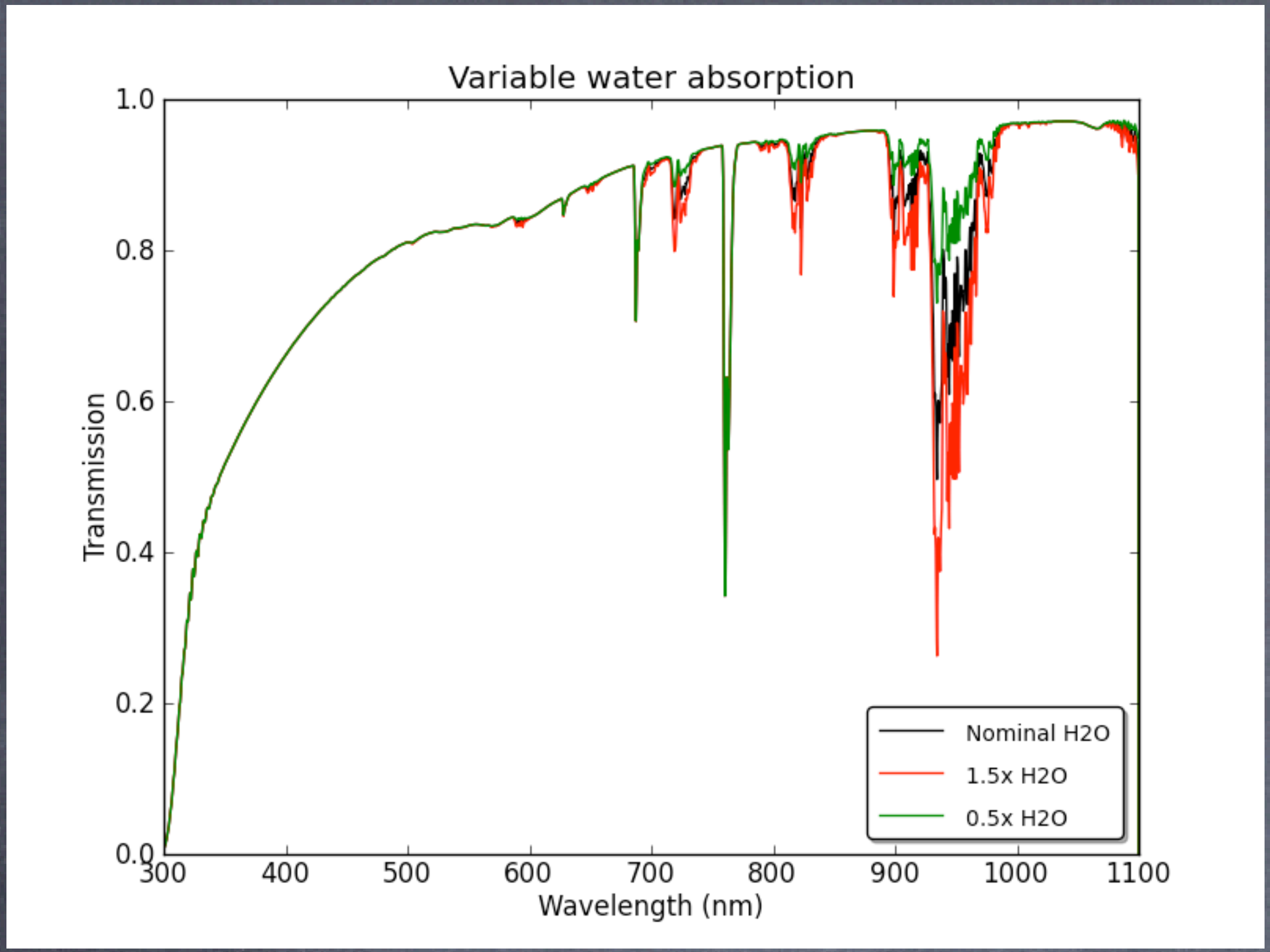
Use self-calibration to determine 'gray' zeropoints

Flowchart of Internal Photometric Calibration

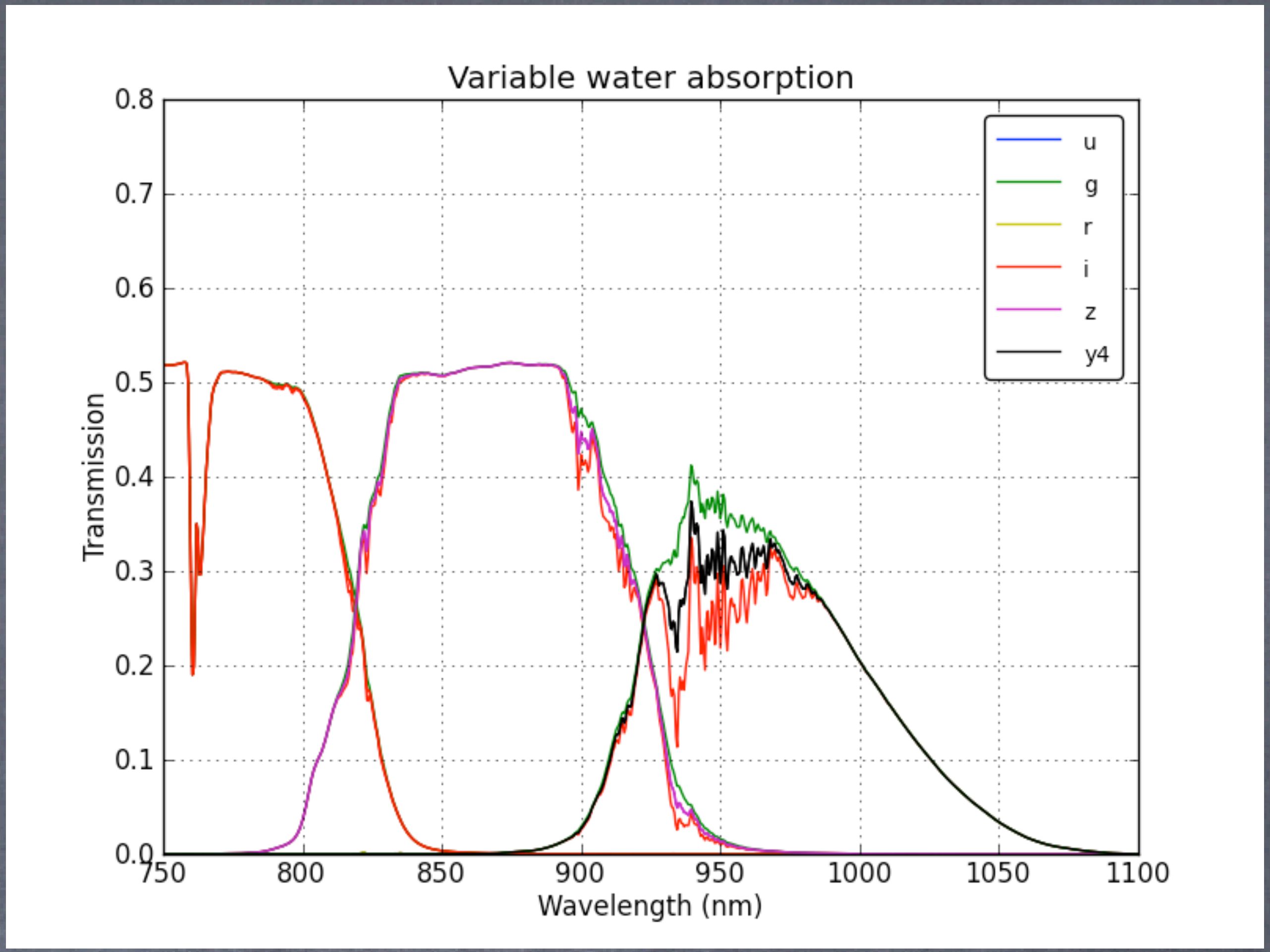


Hardware vs Atmosphere

- Consider gray scale and color-dependent photometric shifts separately (because of self-calibration & clouds, and because vary on different time and spatial scales)
- Compare color-dependent photometric shifts from hardware vs atmospheric changes
  - Factor of 3 in water absorption
  - 1% filter shift

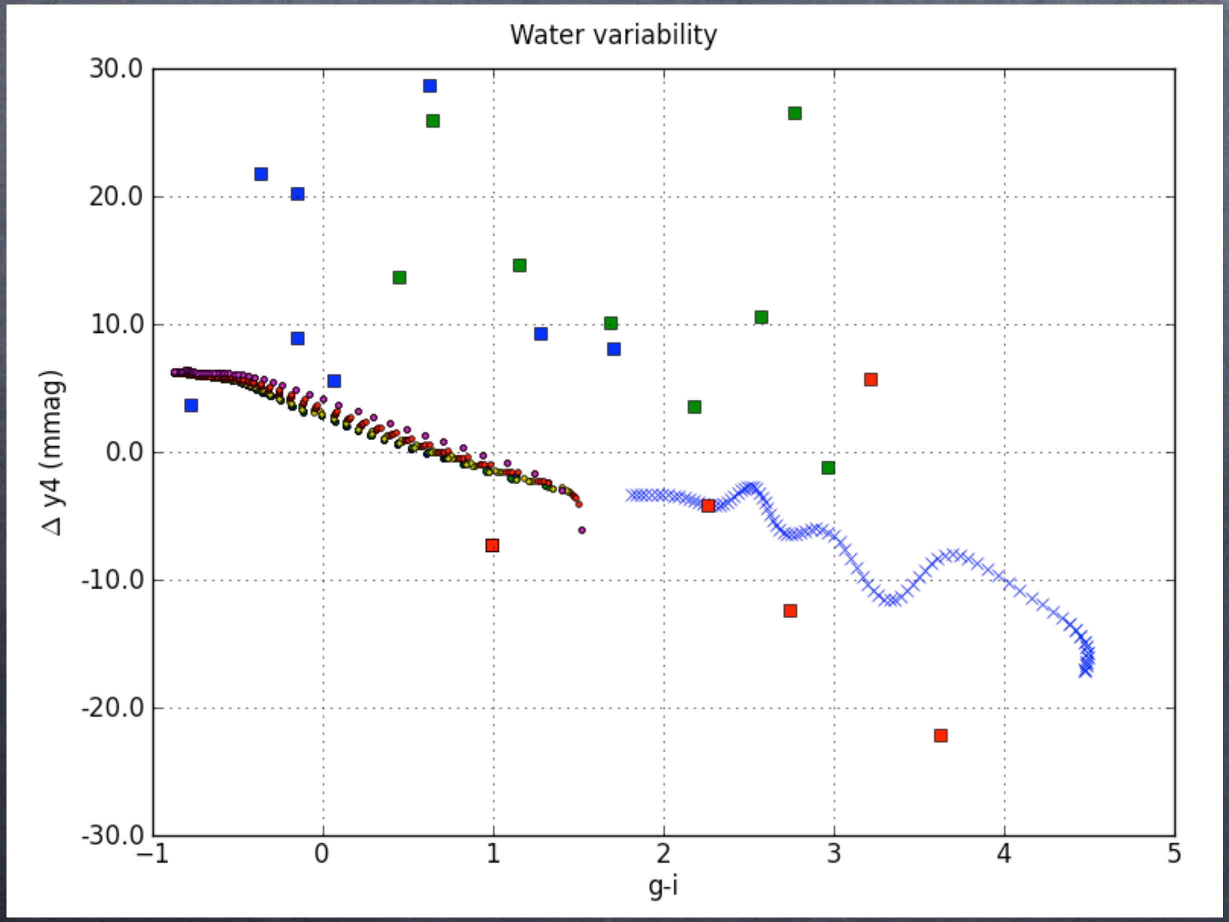


Variable water absorption
Transmission
Wavelength (nm)
Nominal H2O
1.5x H2O
0.5x H2O

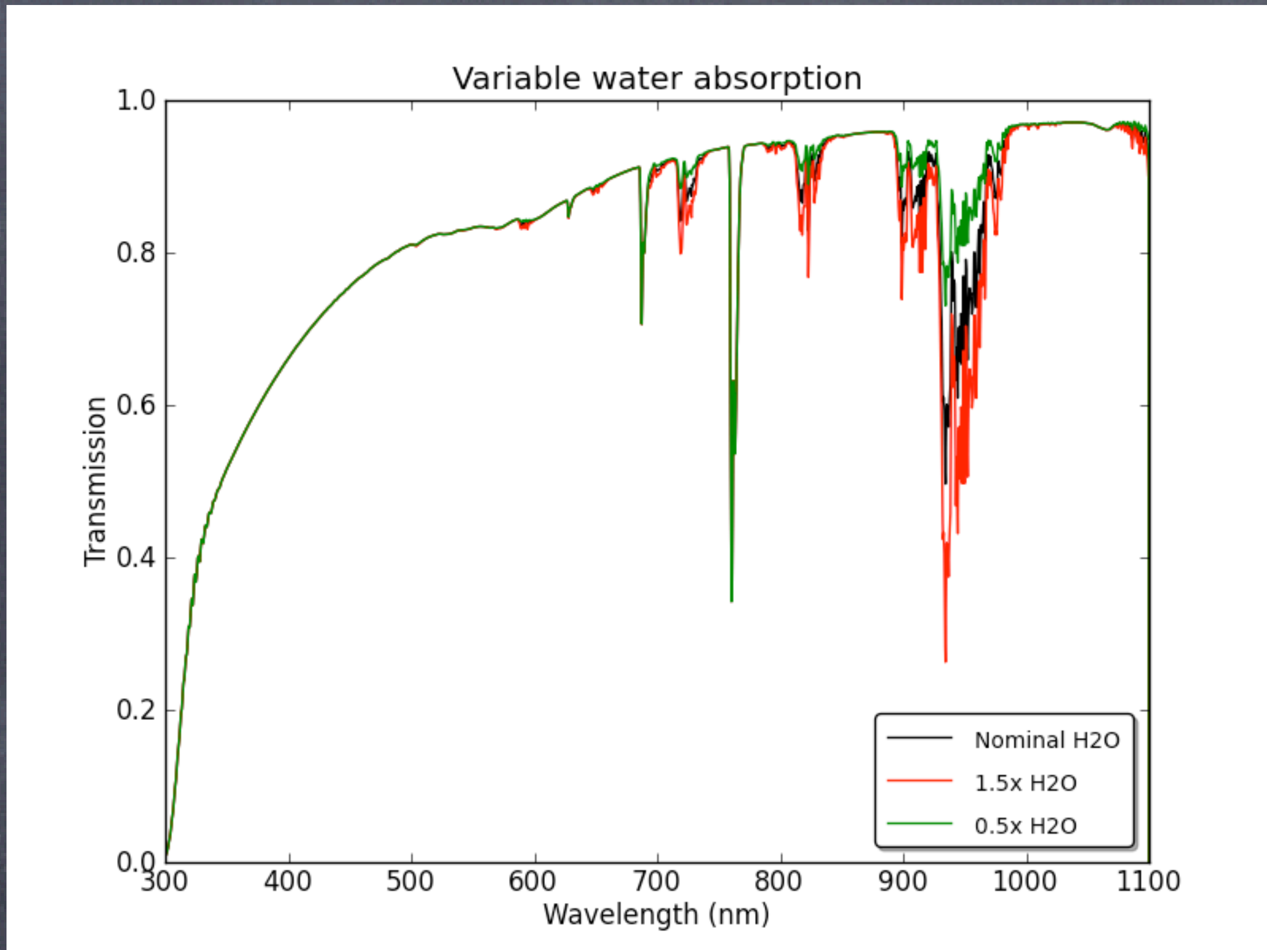


Variable water absorption
Transmission
Wavelength (nm)
u
g
r
i
z
y4

60 mmag



Water variability
Δ y4 (mmag)
g-i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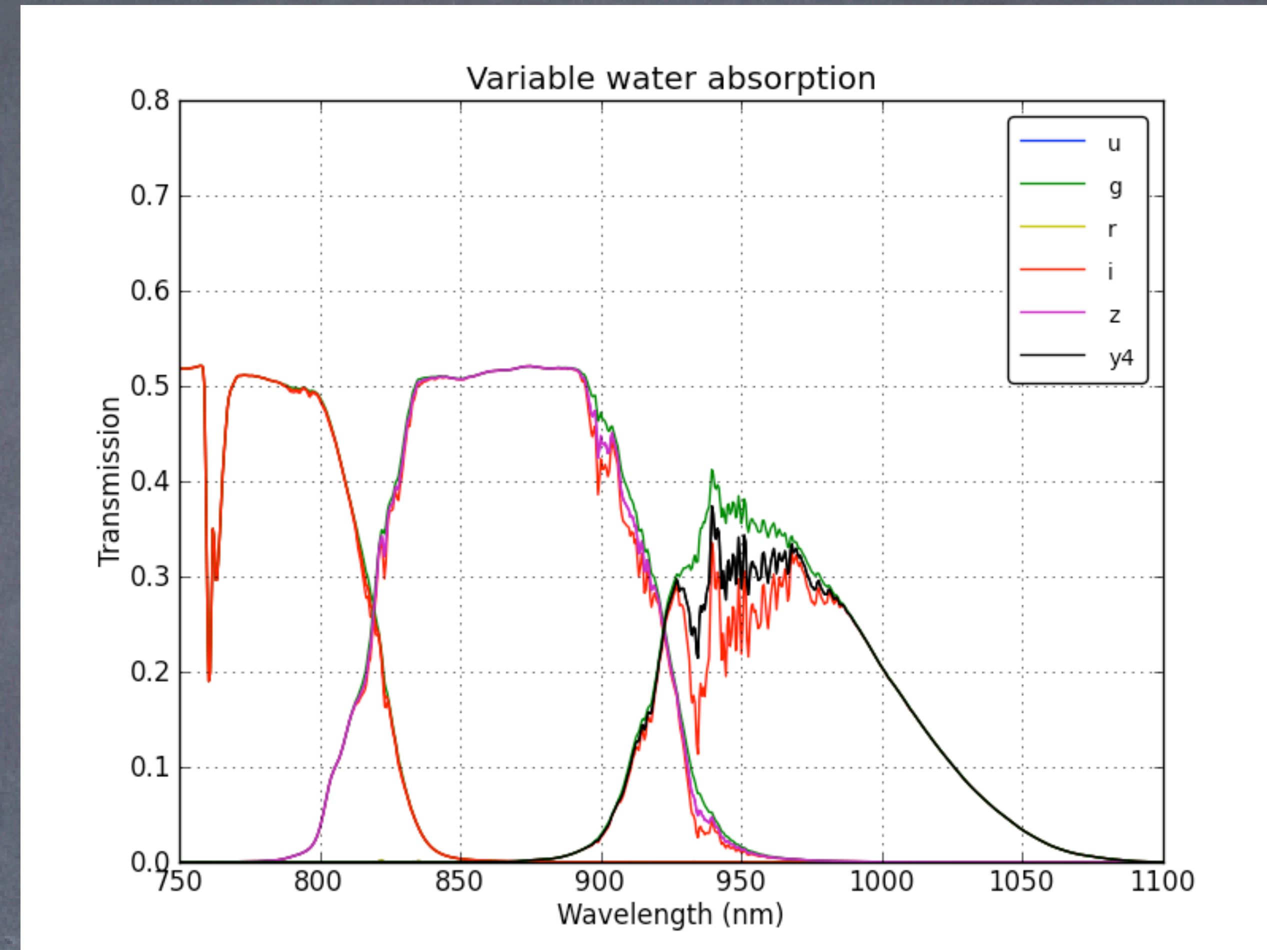
Variable water absorption
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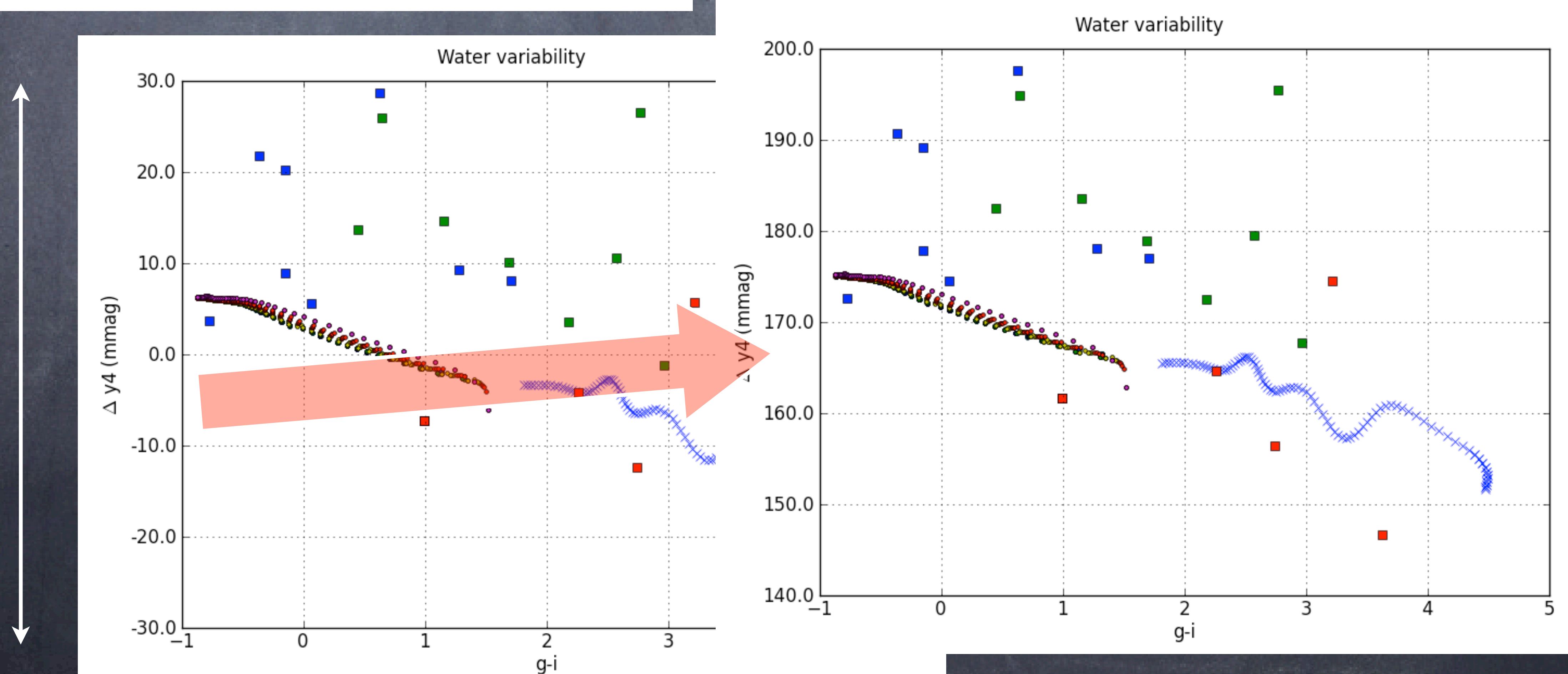
Water variability
Δ y4 (mmag)
g-i
Water variability
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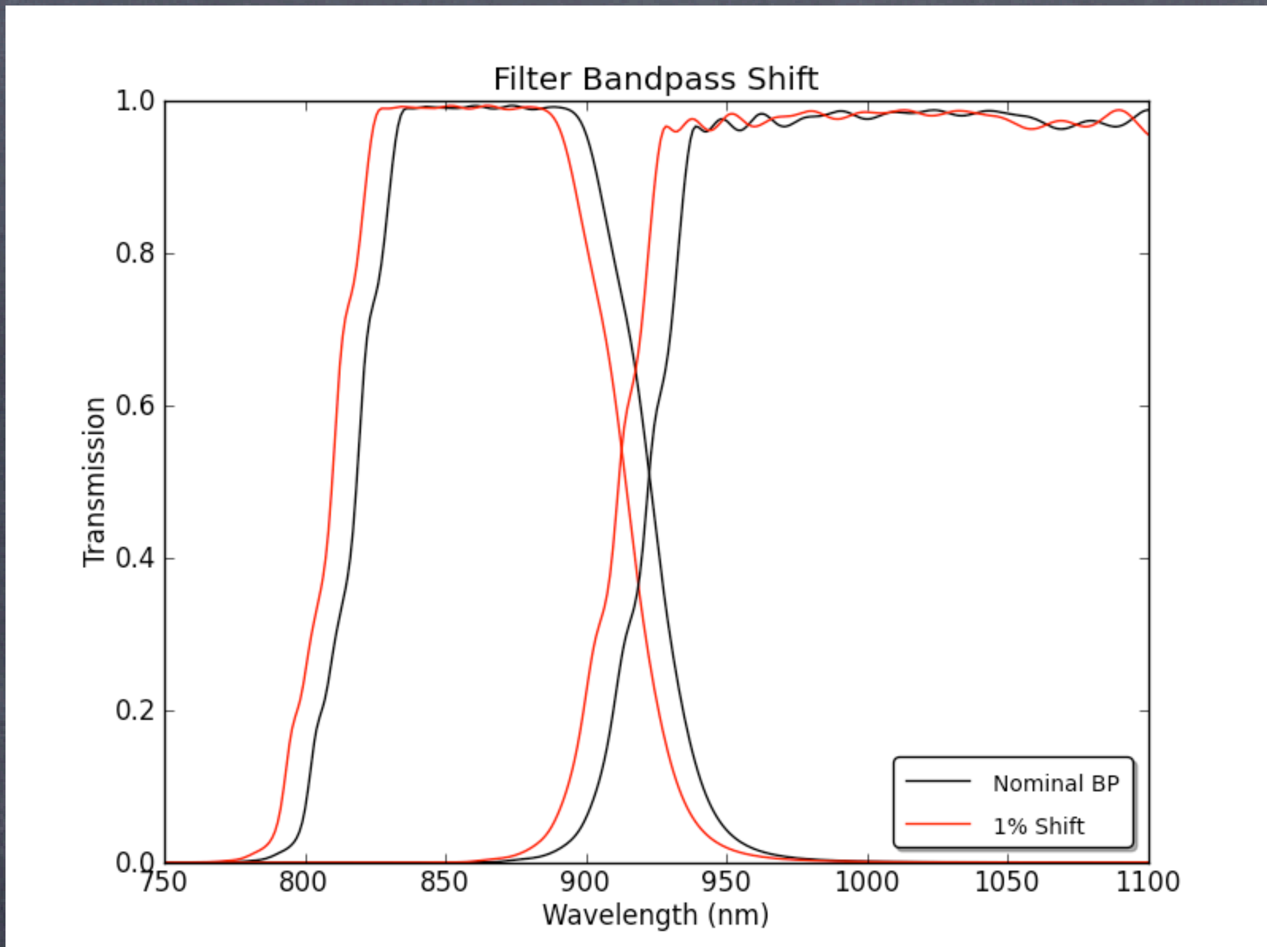
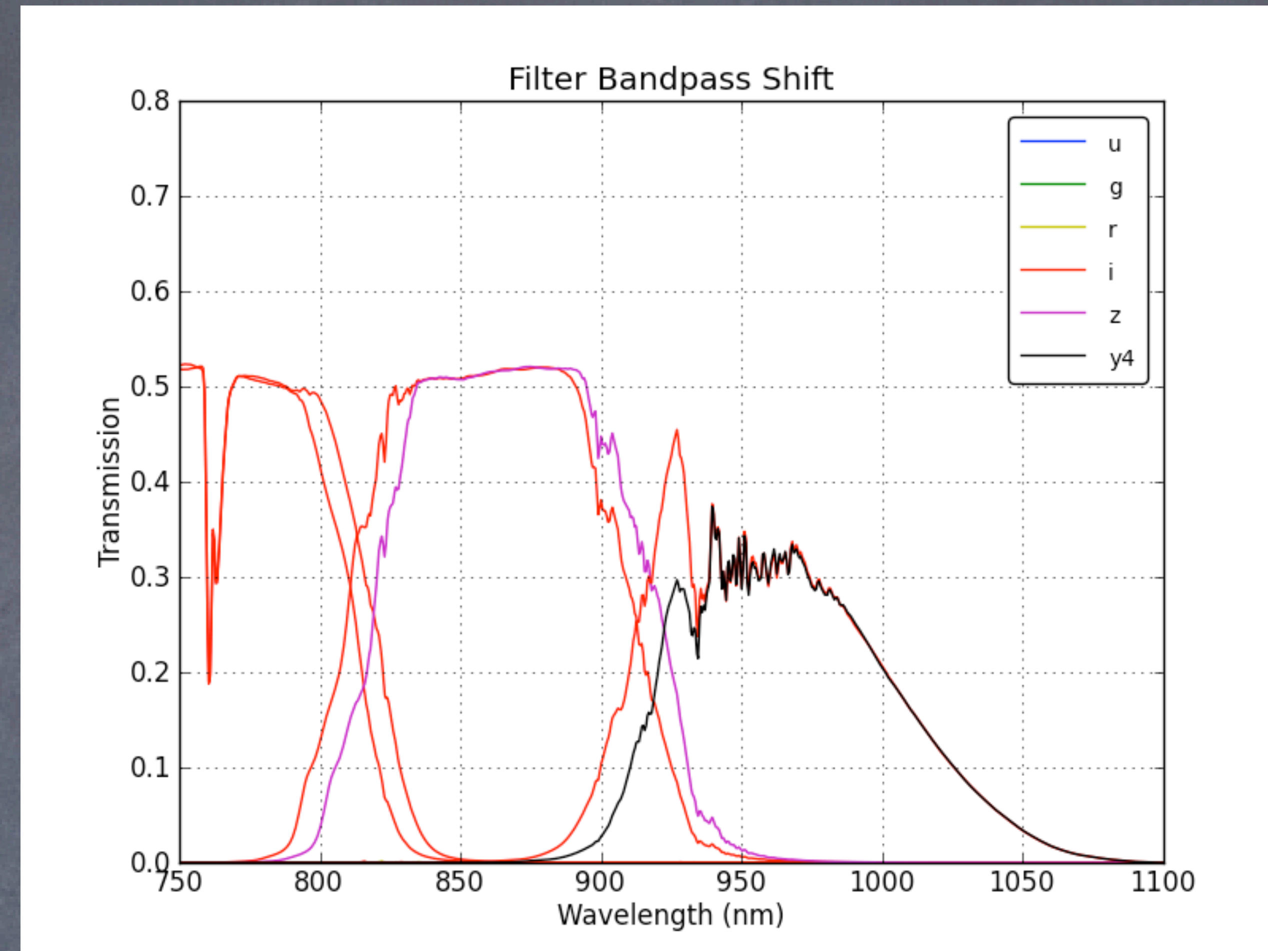
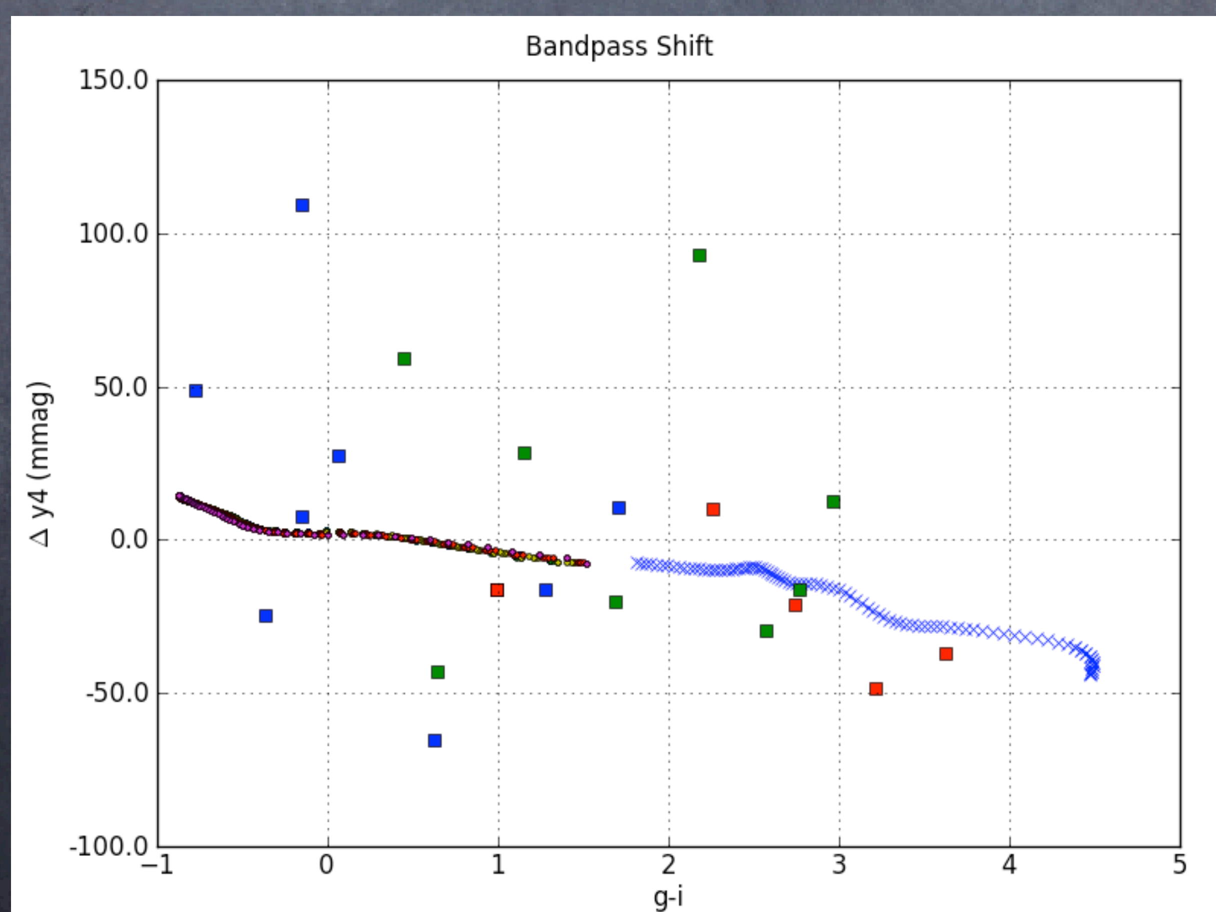




250 mmag



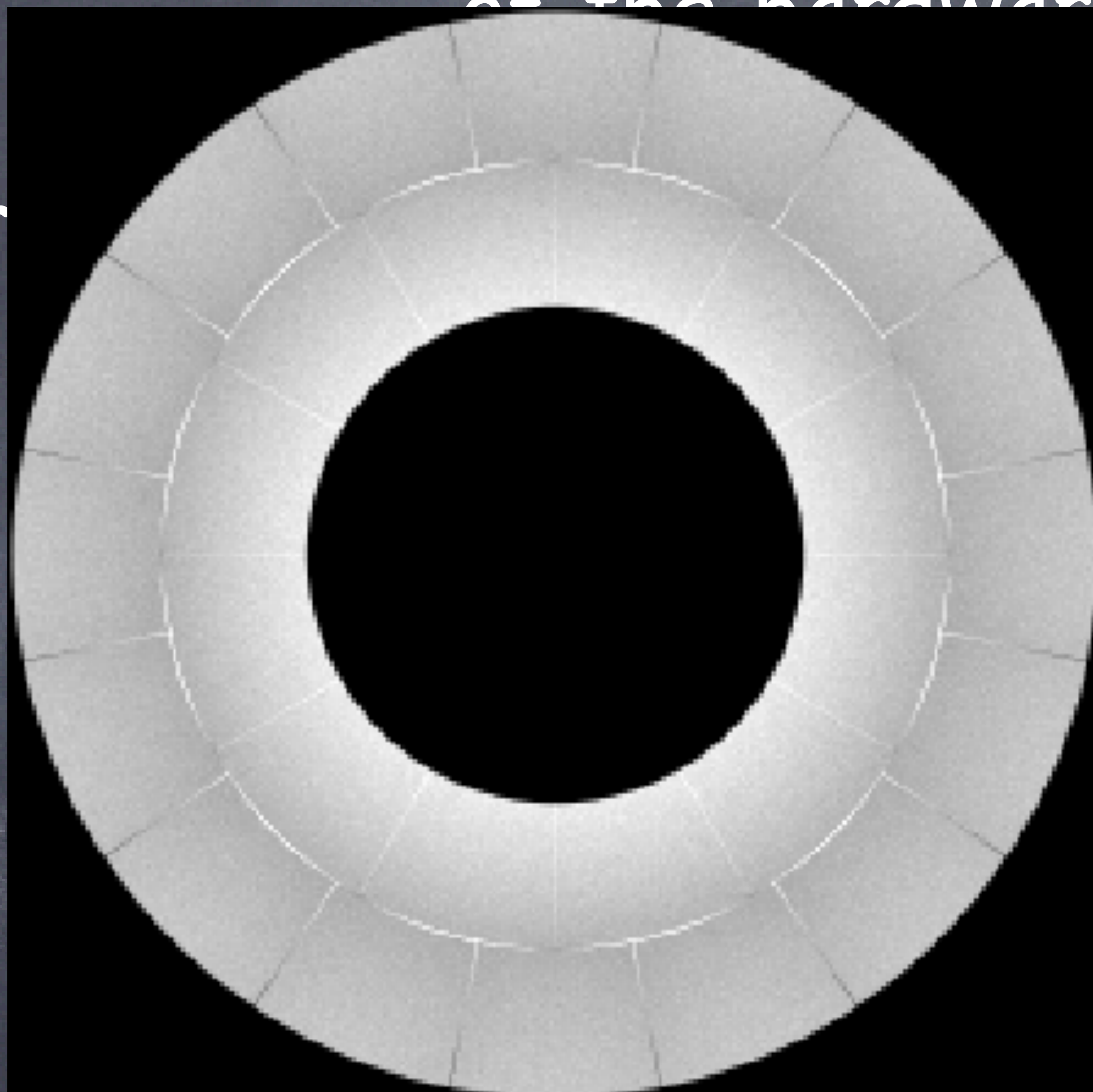
Color dependent effects of a filter shift larger than expected atmospheric effects. See improvement in SNLS with color-dependent flat field (Regnault et al 2009).
But, still need to measure atmosphere transmission curve.

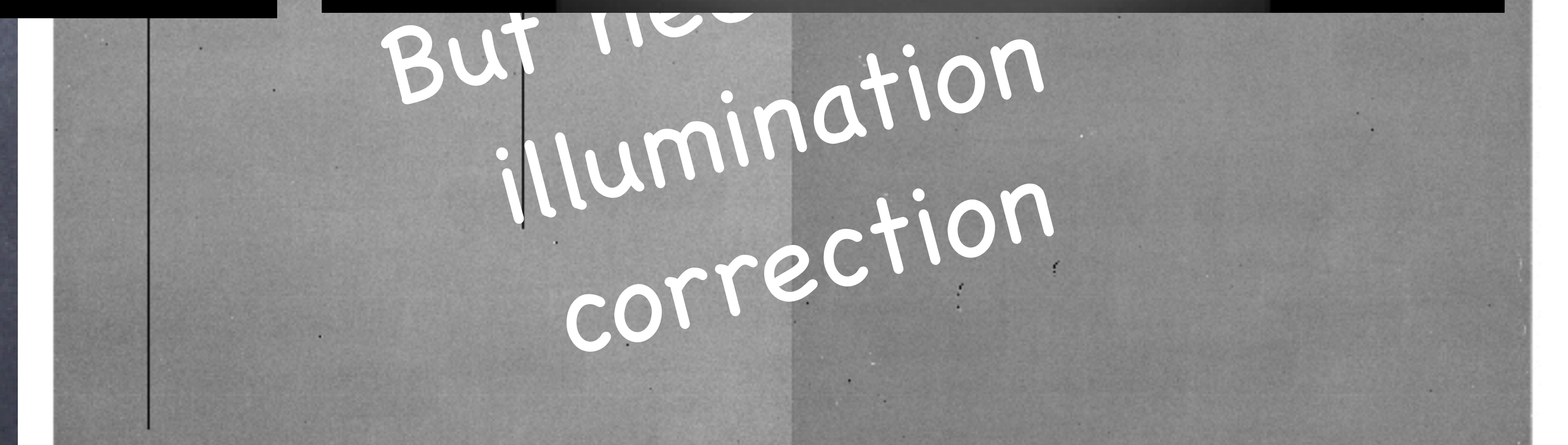
Measuring the normalization of the hardware throughput

- **Broad-band flat fields**
  - Correct for **wavelength-independent** effects (normalization of hardware throughput across x/y)
  - Sensitivity variations, dust in optical path ...
  - Small spatial scales
  - Nightly time scales
- White light flat
- Apply directly to images

Measuring the normalization of the hardware throughput

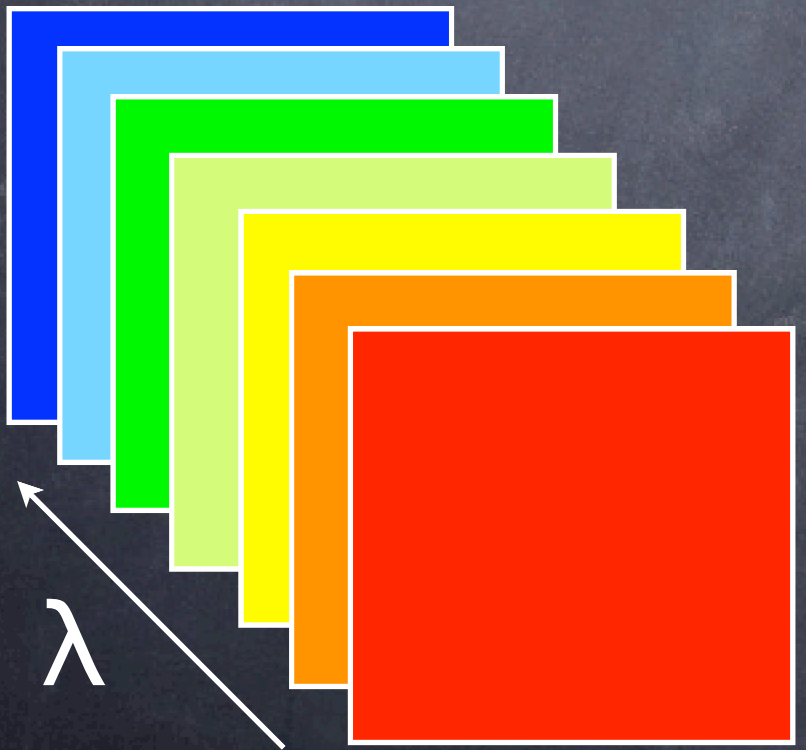
- **Br**
  - Nightly time scales
- White light flat
- Apply directly to images



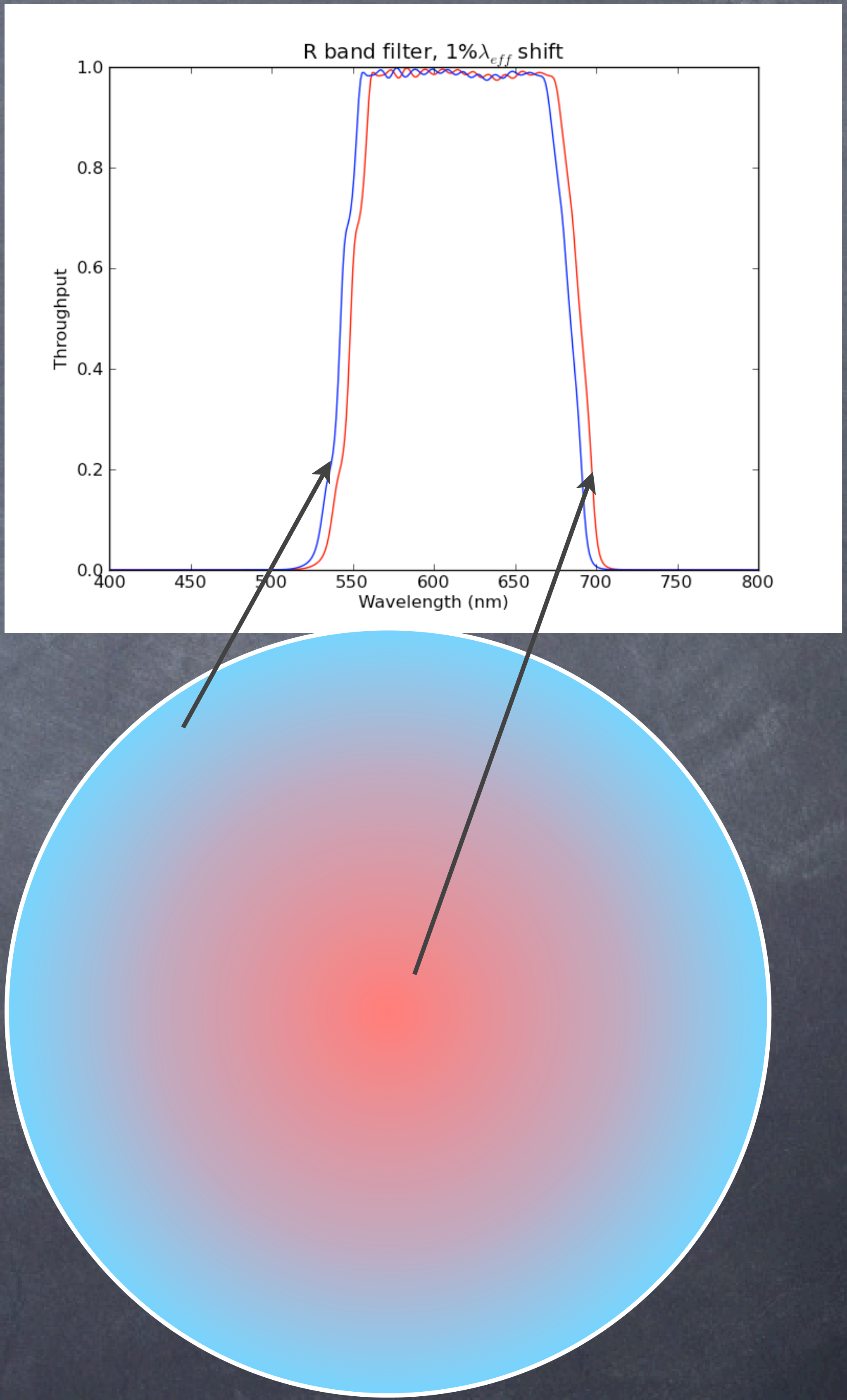


Measuring the shape of hardware response

- **Narrow-band flat fields**
  - Correct for **wavelength-dependent** effects (shape of hardware throughput)
  - Filter non-uniformity, coating changes with age ..
  - Larger spatial scales
  - Monthly time scales
- Tunable laser + NIST photodiode

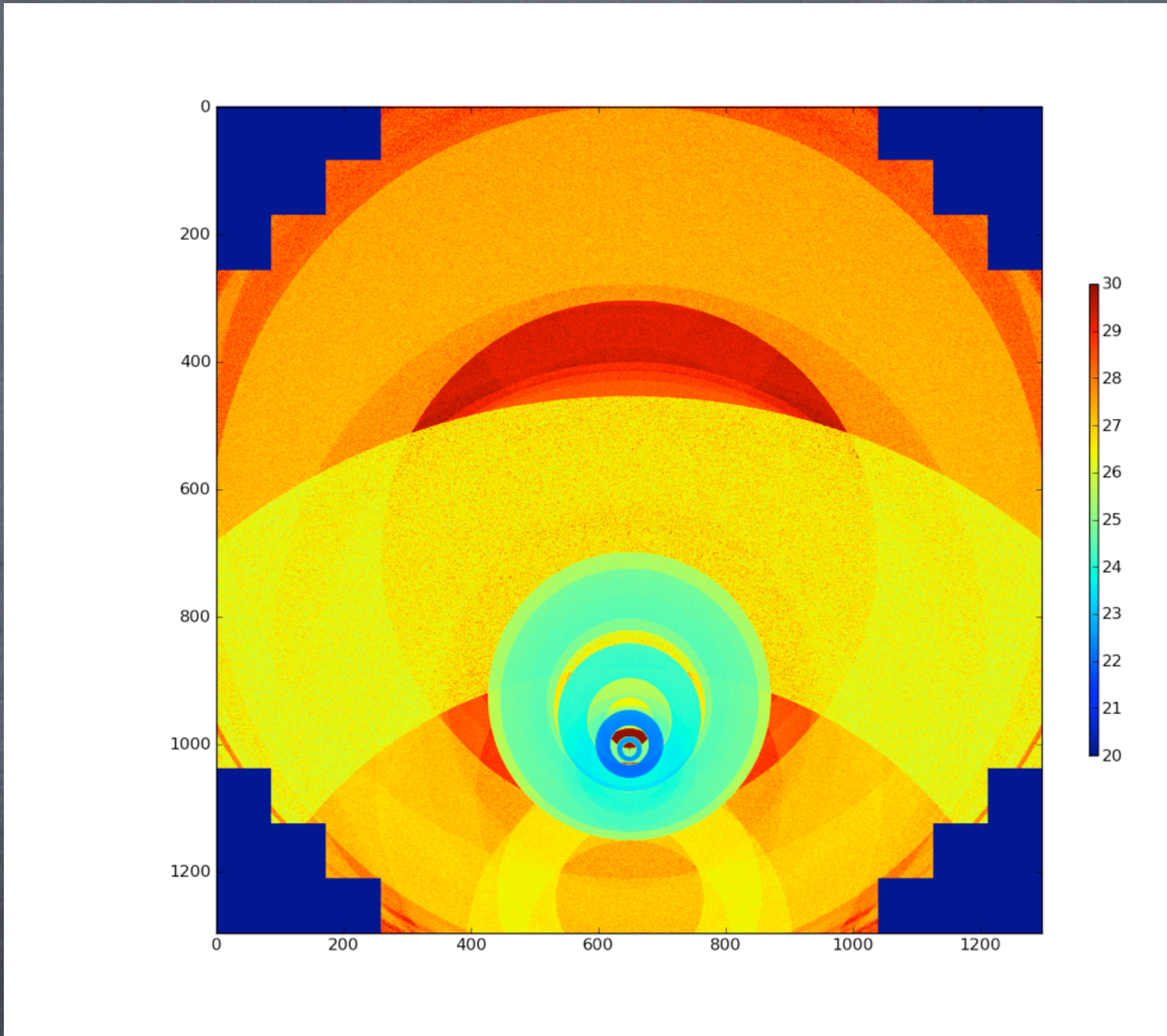


Data cube of narrow-band flat fields



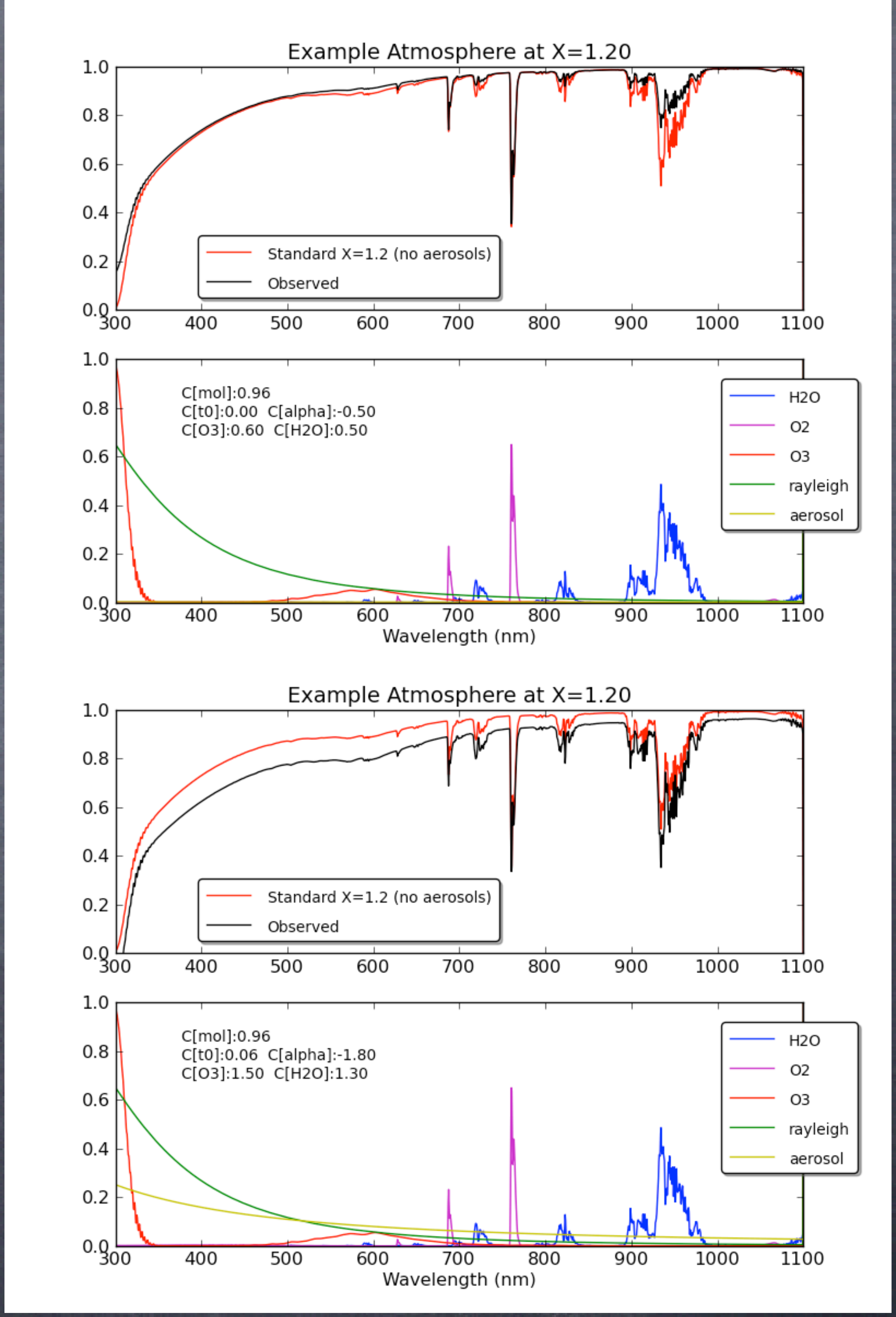
Also need IC for narrow-band flats

- Primary problem here is ghosting (particular near edges of bandpass)
  - Ghosting model may be sufficient for correction
  - Collimated or otherwise point-like sources?

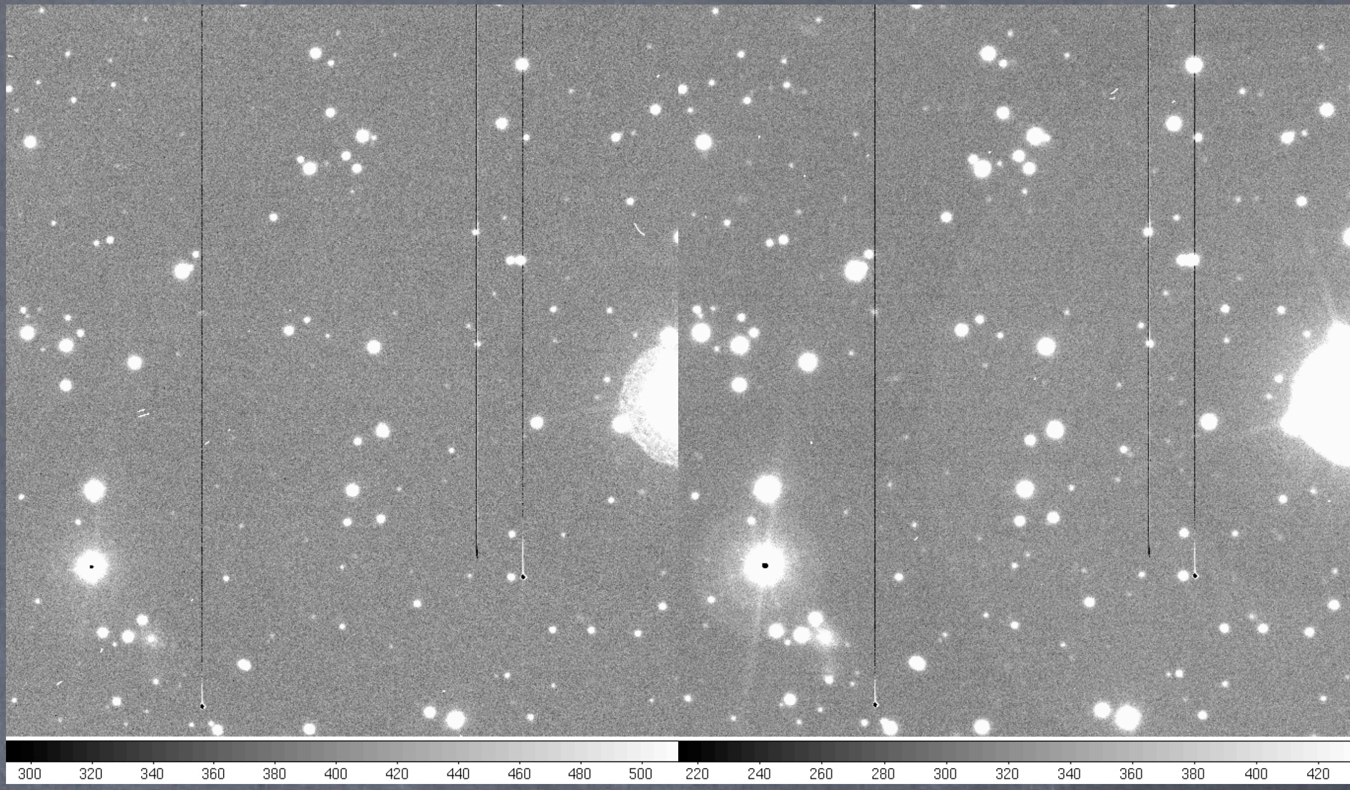


Measuring the shape of the atmospheric throughput curve

- Spectra from **auxiliary telescope**
  - Correct for **wavelength-dependent** atmospheric absorption (shape)
  - Aerosol scattering, water absorption ...
  - Slow & predictable spatial variation
  - 20 minute timescales
- Combine models of stellar spectra, MODTRAN templates, and model of atmosphere behavior
  - Can bootstrap stellar SEDs
- See Burke et al 2010



Measuring the normalization of the atmospheric throughput



- **Self-calibration procedure**
  - Correct for clouds (& more)
  - CCD to few PSF spatial scales
  - Visit time scales
- Process: pre-correct for color-dependent effects for 'calibration stars', then invert large matrix to find zeropoints for each observation
  - Matrix is large (10^8x10^8) but sparse - only about 10^10 non-zero values per band
- Similar to SDSS ubercal but different model assumptions

$$\chi^2 = \Sigma_{ij} \left(\frac{m_{b,ij}^{std} - m_{b,ij}^{model}}{\sigma_{b,ij}^{std}} \right)^2$$

$$m_{b,ij}^{model} = m_{b,i}^{best} - \delta z_{b,j}$$

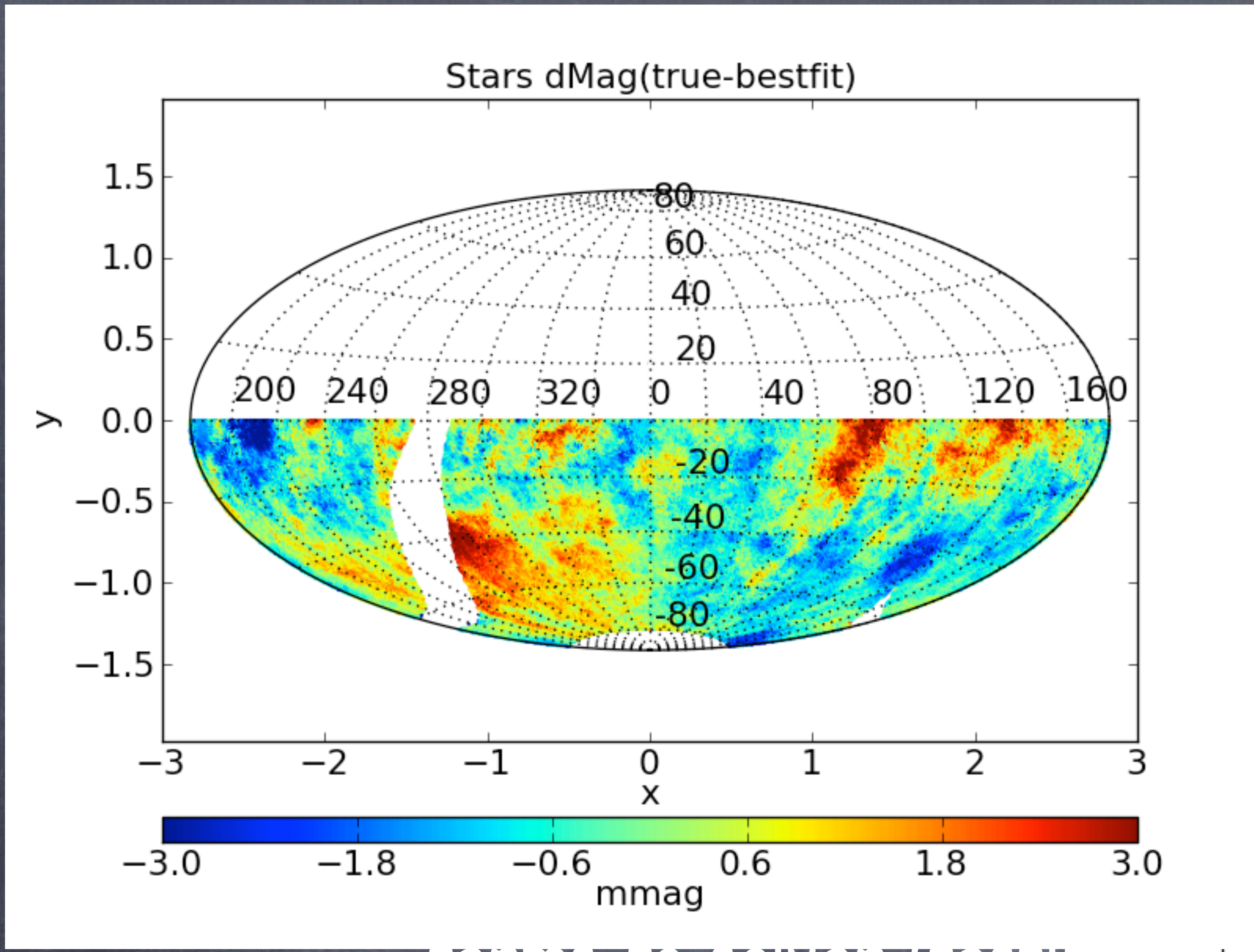
Self-calibration simulations

- Current test model simulates stars with magnitude errors due to
  - Shot noise, DM measurement errors, variable filter bandpasses, jitter in filter position, atmospheric transmission errors, gain variation, illumination correction errors, cloud structure
  - Use GALFAST & Kurucz models to generate MS stars across the sky with appropriate SEDs & magnitudes
    - Can add variability with Kepler-like distribution
  - Simulations using 1M - 20M stars
- Combine with pointing history from Operations Simulation
  - Typically testing with 2 years (out of 10 possible), one band
  - Have also tested various dither patterns
- Invert matrix (testing various solvers)

Self-calibration simulations

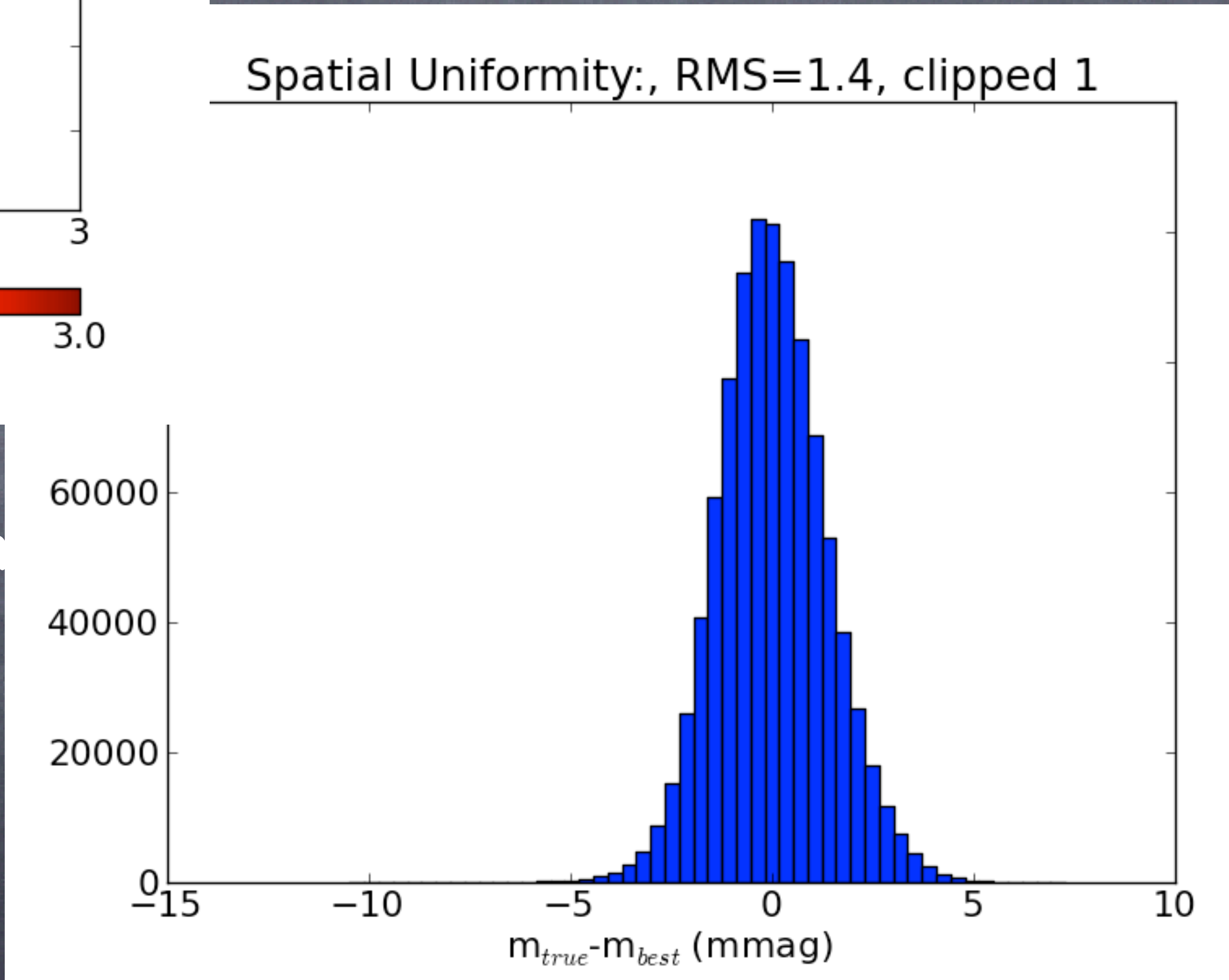
- Solve for zeropoints for each calibration patch (scales between 1 CCD and 1/4 FOV) and best-fit magnitude for each calibration star
  - Currently usually single zeropoint, but can add other terms to solver (testing illumination correction)
- Starting point simulation
  - 1M stars, 2 years, no clouds, no IC error

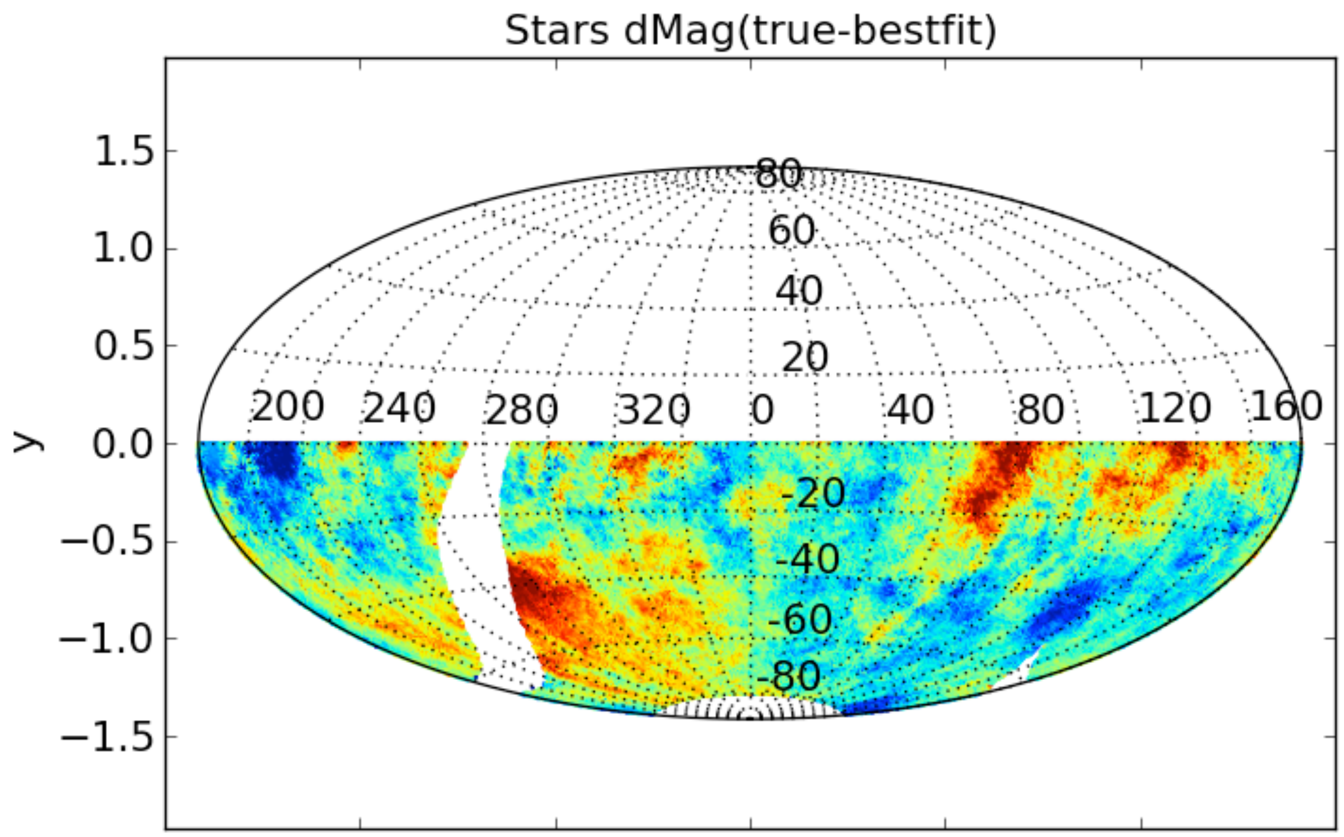
simulations

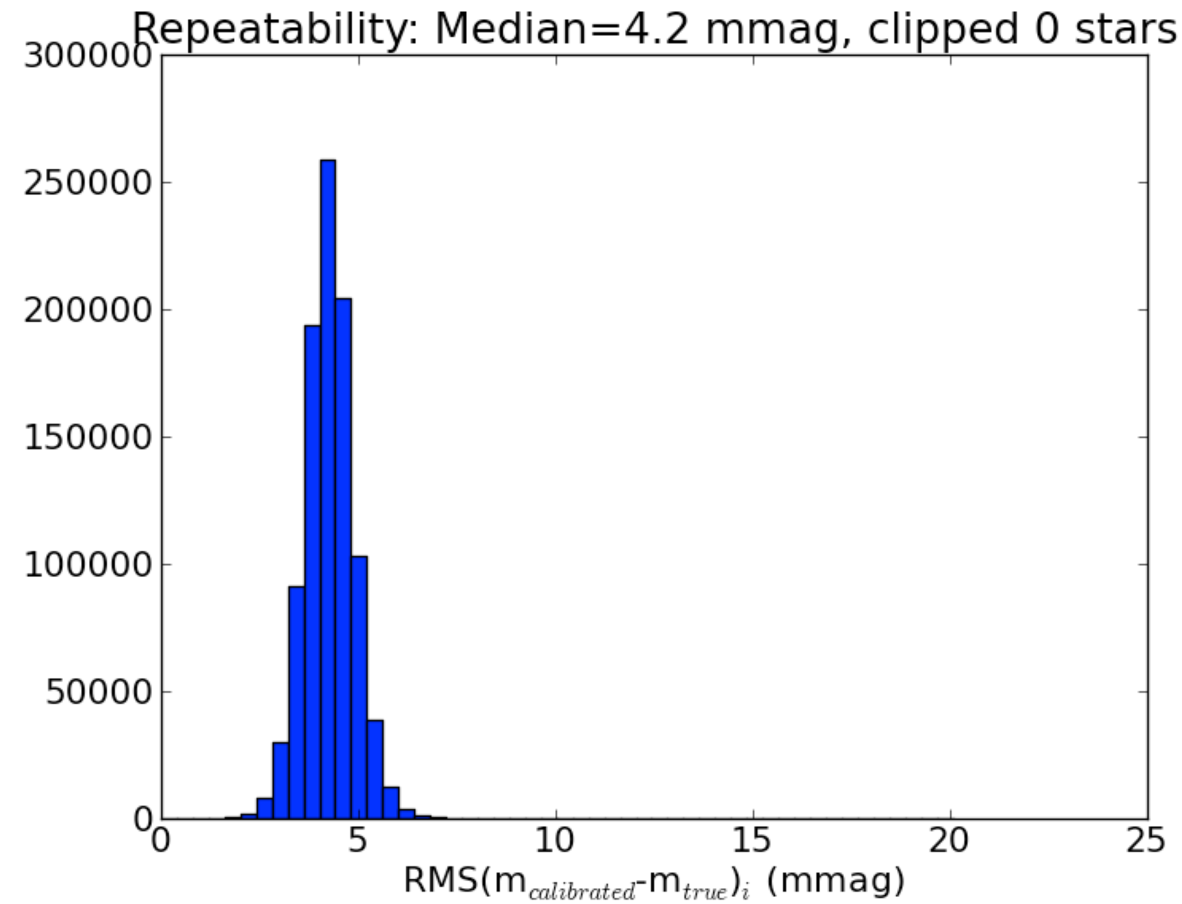


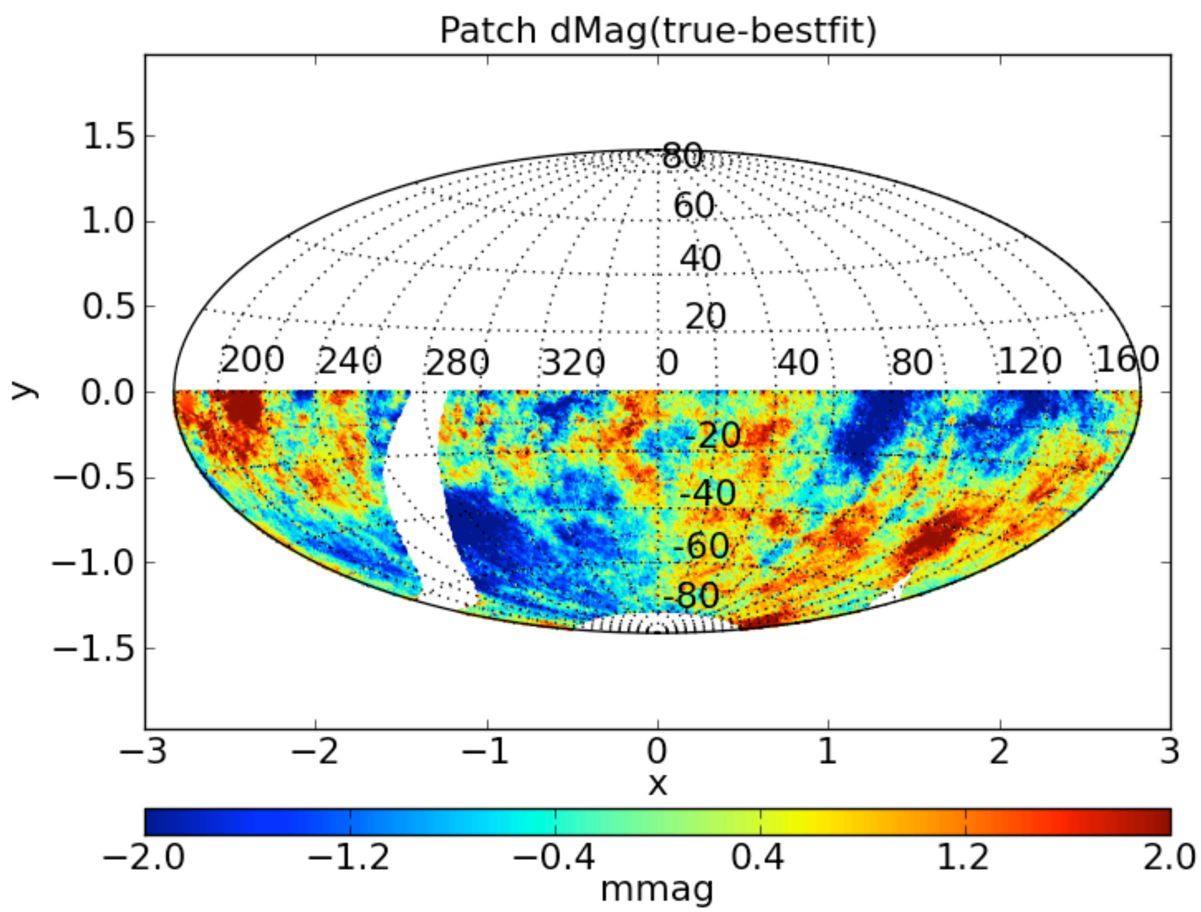
terms to solver (testi

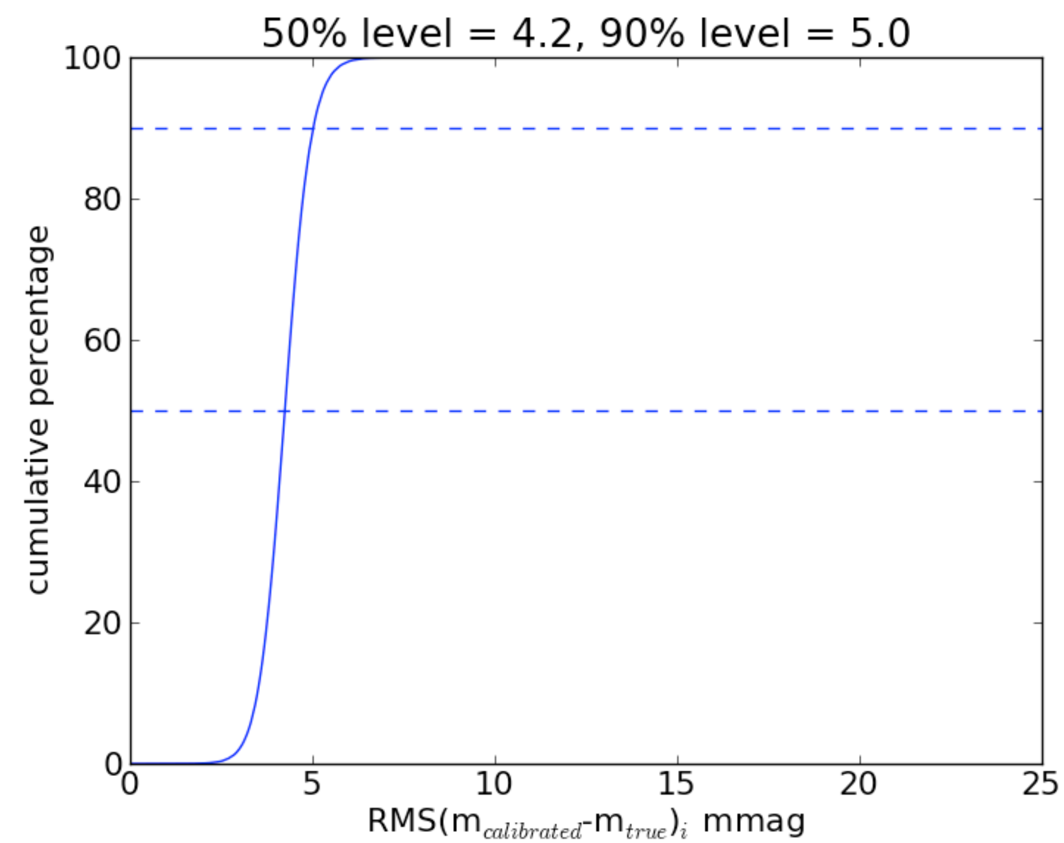
- Starting point simulation
  - 1M stars, 2 years, no




Stars dMag(true-bestfit)
y


Repeatability: Median=4.2 mmag, clipped 0 stars
RMS($m_{calibrated}$-m_{true})$_i$ (mmag)

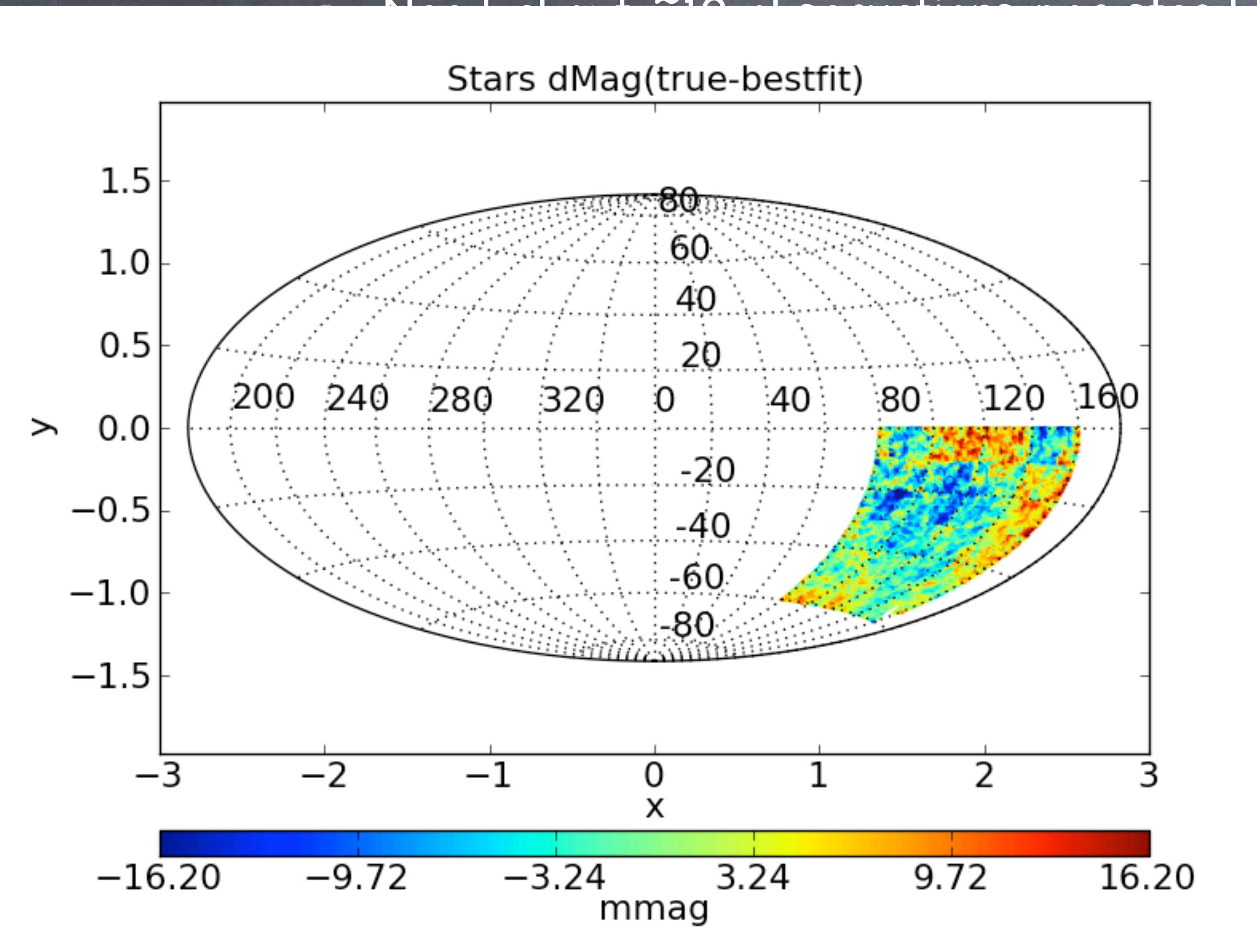

Patch dMag(true-bestfit)
y
x
mmag

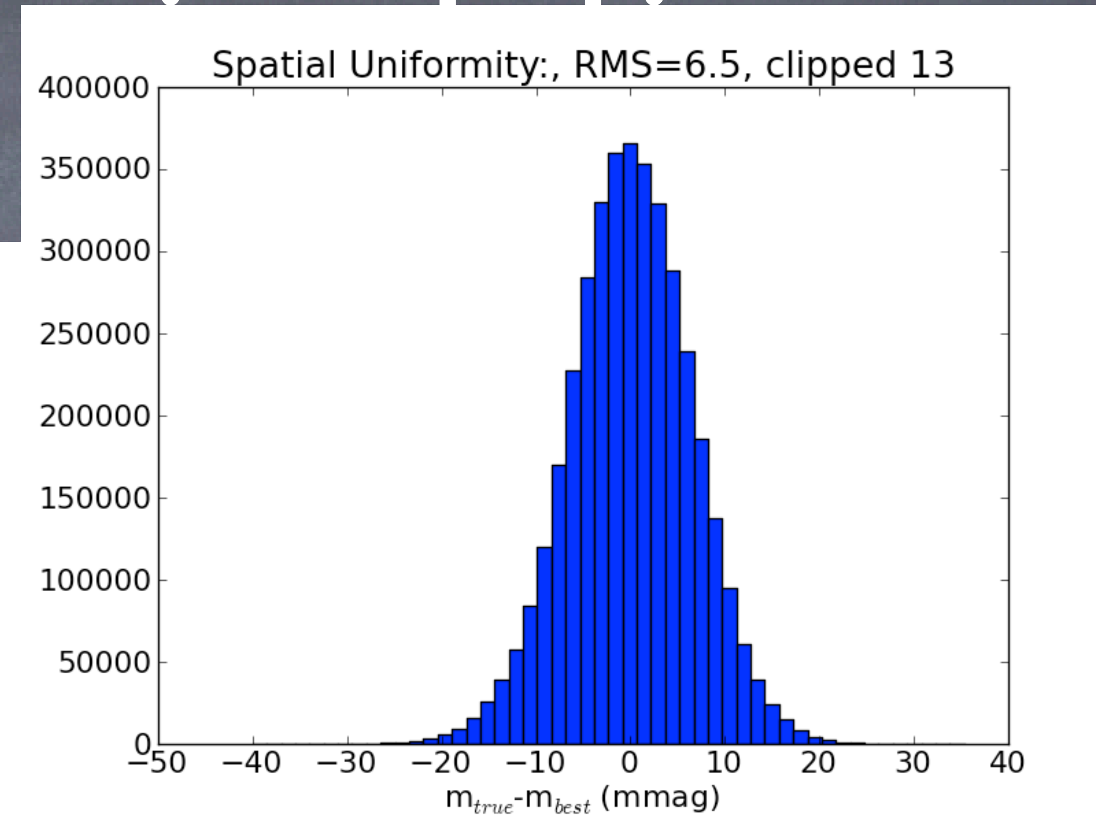

50% level = 4.2, 90% level = 5.0
cumulative percentage
RMS($m_{calibrated}$-m_{true})$_i$ mmag

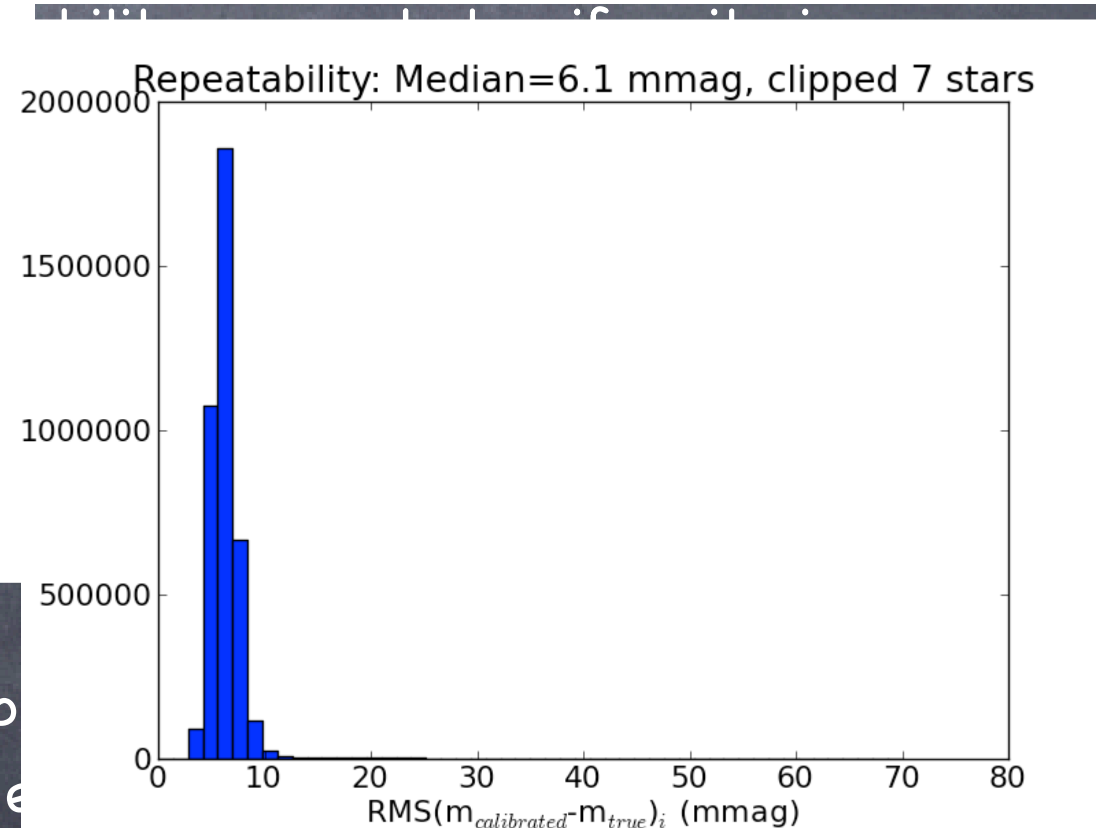
Self-calibration simulations

- Need about ~10 observations per star before converge to requirements
  - Linked across sky
- Expect 100 stars per CCD patch; can calibrate with less*
- Dither patterns (overlap & rotation)
  - As long as good overlap, is fine
- Filter jitter
  - Not a large effect
- DM measurement errors increase repeatability errors but uniformity is okay
  - If non-Gaussian errors, outlier rejection may be important
- Errors reported to selfcalibration solver are important
- Illumination correction errors
  - Seem to calibrate well so far
- Have not added color-dependent terms to model
- Clouds
  - Patch size is important, binning by photometric-icity may help
  - Need more realistic clouds to fully evaluate (and solver improvements)

Self-calibration







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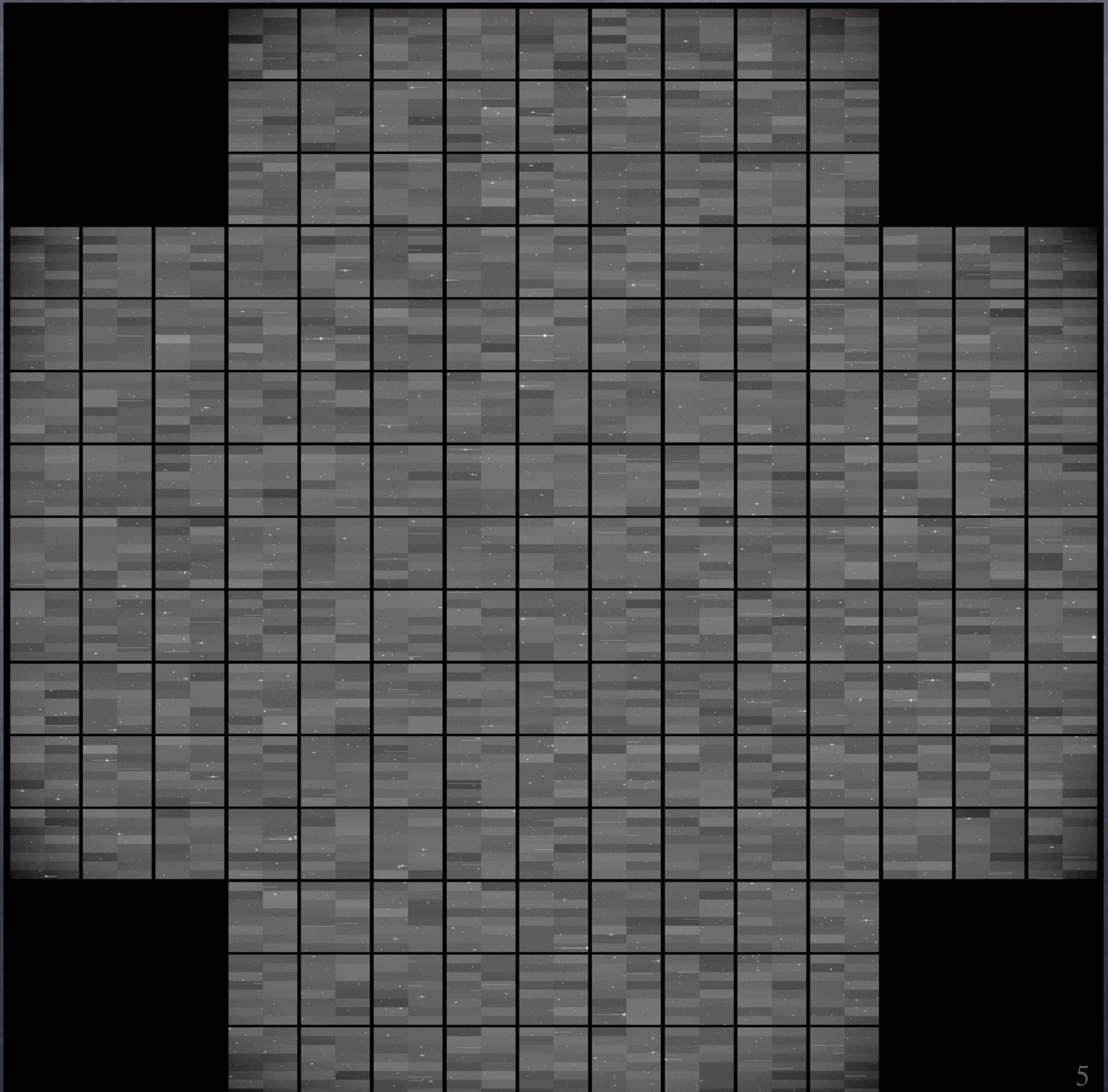
LSST SRD requirements

Internal	Repeatability	5 mmag (0.5%) (7.5 mmag in u/z/y)	RMS in the scatter of repeat measurements of the SAME star is less than 5 mmag. Photometry can be compared over time.
	Uniformity	10 mmag (1%) (20 mmag in u/z/y)	RMS of zeropoint scatter ACROSS THE SKY is less than 10 mmag. Photometry can be compared across the sky.
External	Band-to-Band	5 mmag (0.5%) (10 mmag for colors including u)	Accuracy of zeropoint values in each band. Measurements in one filter can be tied to other filters.
	Absolute zeropoint	10 mmag (1%)	Ties LSST photometry to an external, physical scale. Measurements can be compared against models.

Summary

	Hardware	Atmosphere	External calibration
Normalization (wavelength-independent)	Broad band flat fields	Self-calibration procedure using many epochs of observations	Well-studied spectro-photometric standards (WDs)
Shape (wavelength-dependent)	Narrow band flat fields	Auxiliary telescope + spectrograph	Well-studied spectro-photometric standards (WDs)

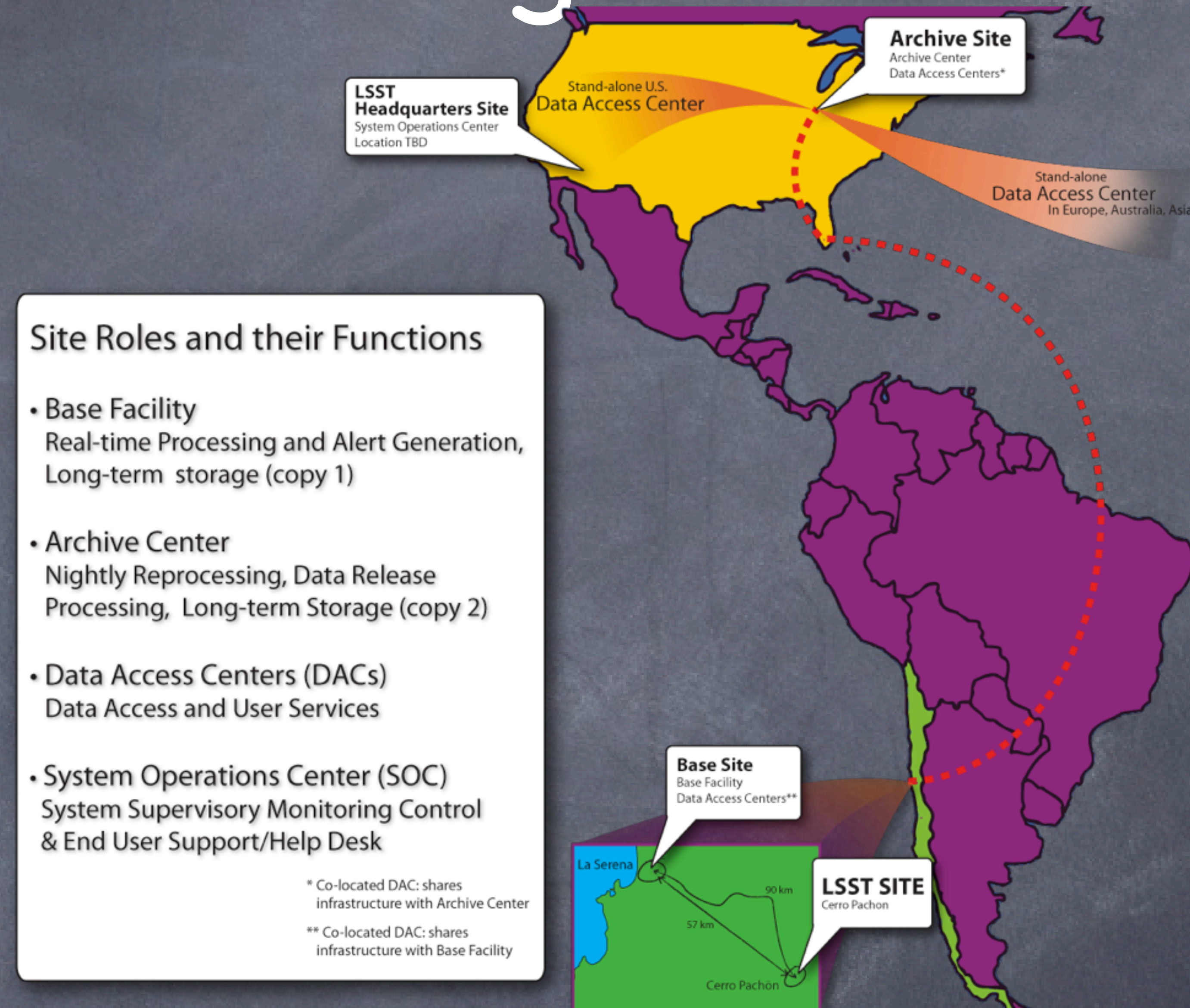
Other
simulations:
OpSim
Catalogs
ImSim



LSST Data Management

Nightly Operations :
Each 15s exposure =
6.44 GB (raw)
2x15s = 1 visit,
~800 visits/night

Release "Alerts" within
60 seconds
(~10^6 per night)



Daily Operations:
More processing (QA/MOPS)
Transfer 15 TB of image data
to US.
(+200 PB of image data over
10 years)

At Data Archive:
6-months to 1 year reprocessing of all data.
Generates calibrated, queryable catalogs:
+20 PB end of 10 years
Generates processed images:
+200 PB end of 10 years